THE PRODUCTION ENGINEER

THE JOURNAL OF THE INSTITUTION OF PRODUCTION ENGINEERS

FEBRUARY 1961

THE PRODUCTION ENGINEER

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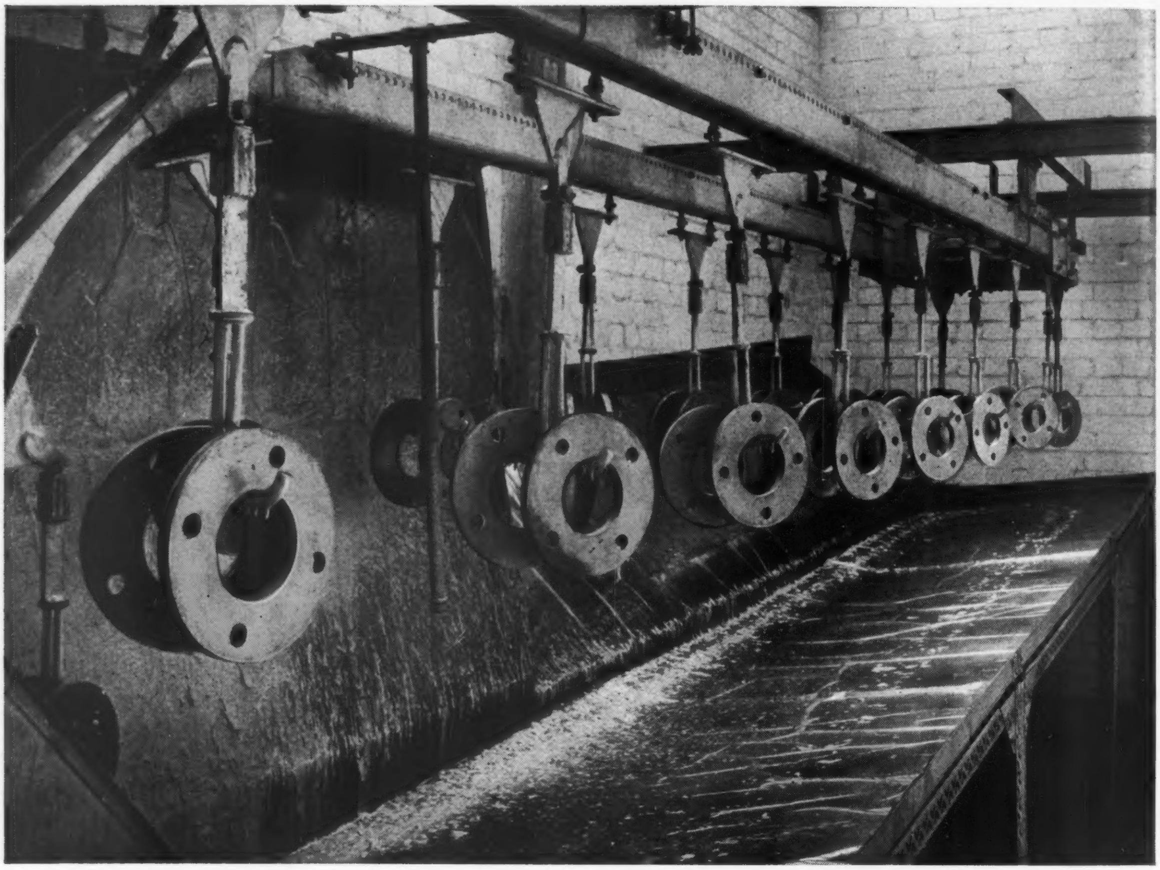

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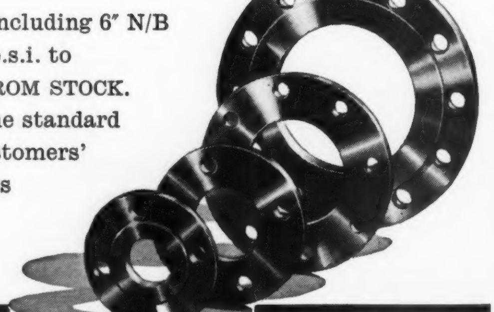

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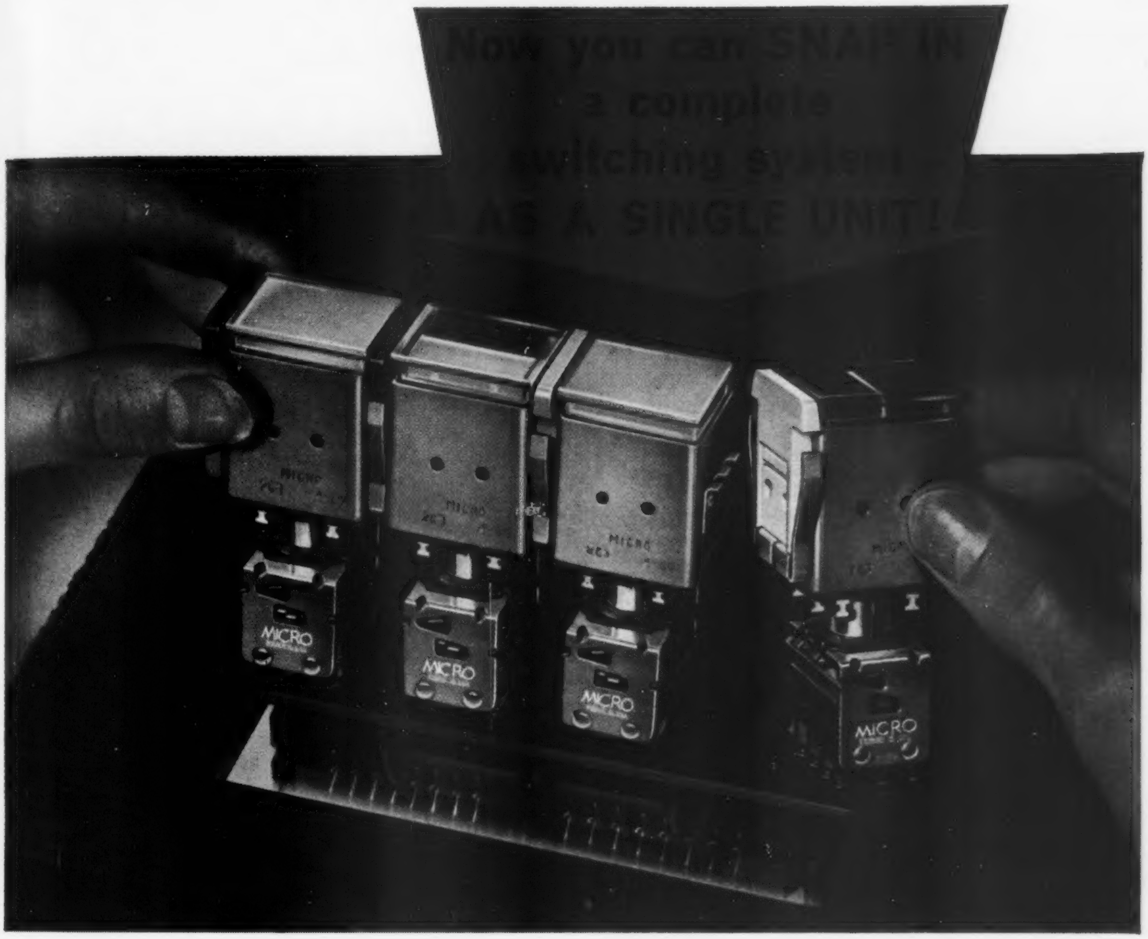
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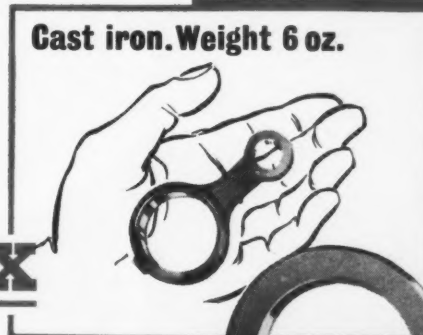

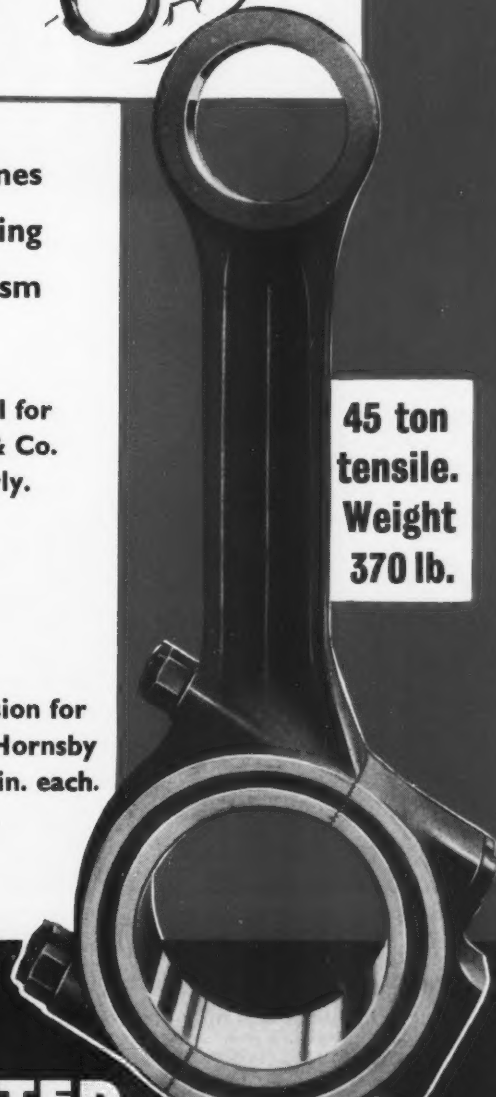

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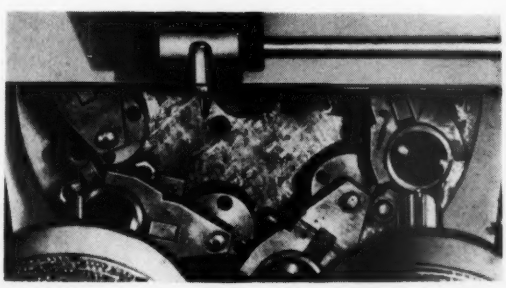

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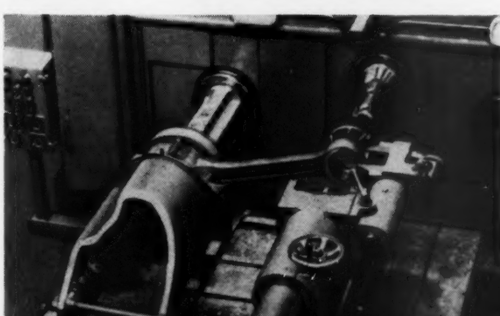

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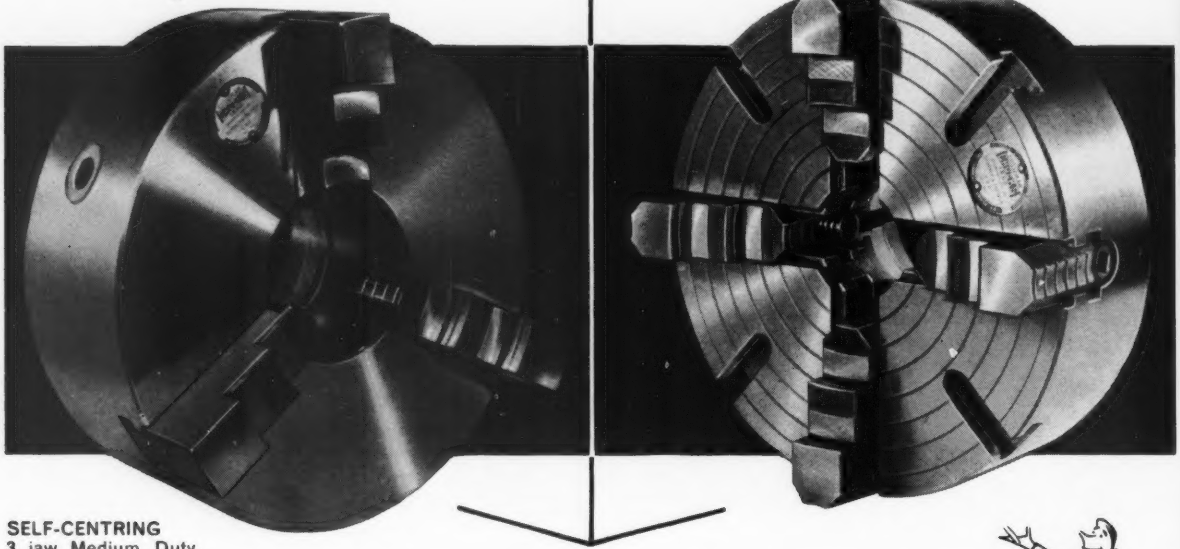

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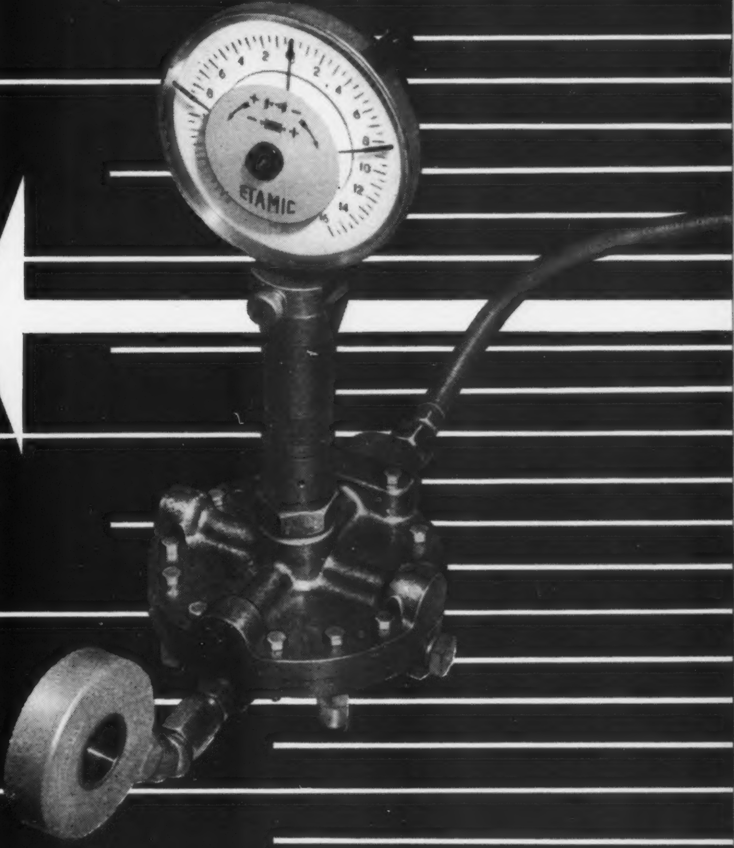

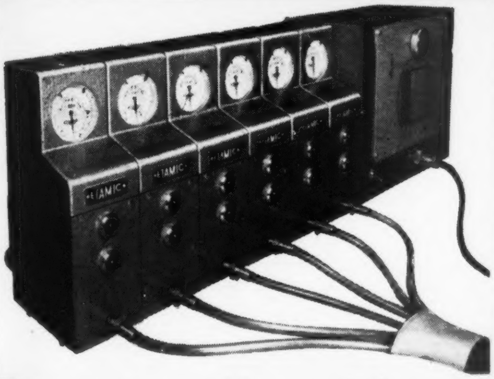

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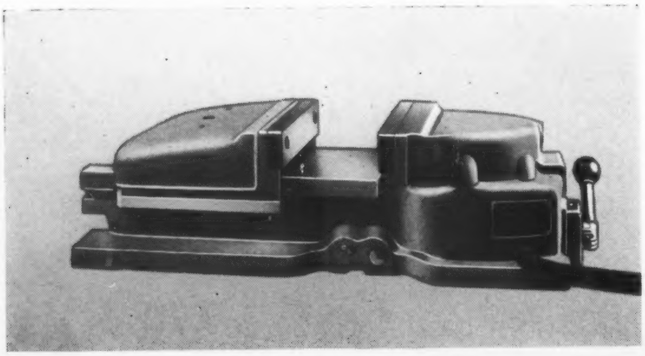

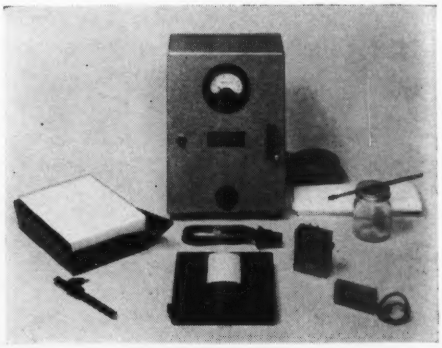

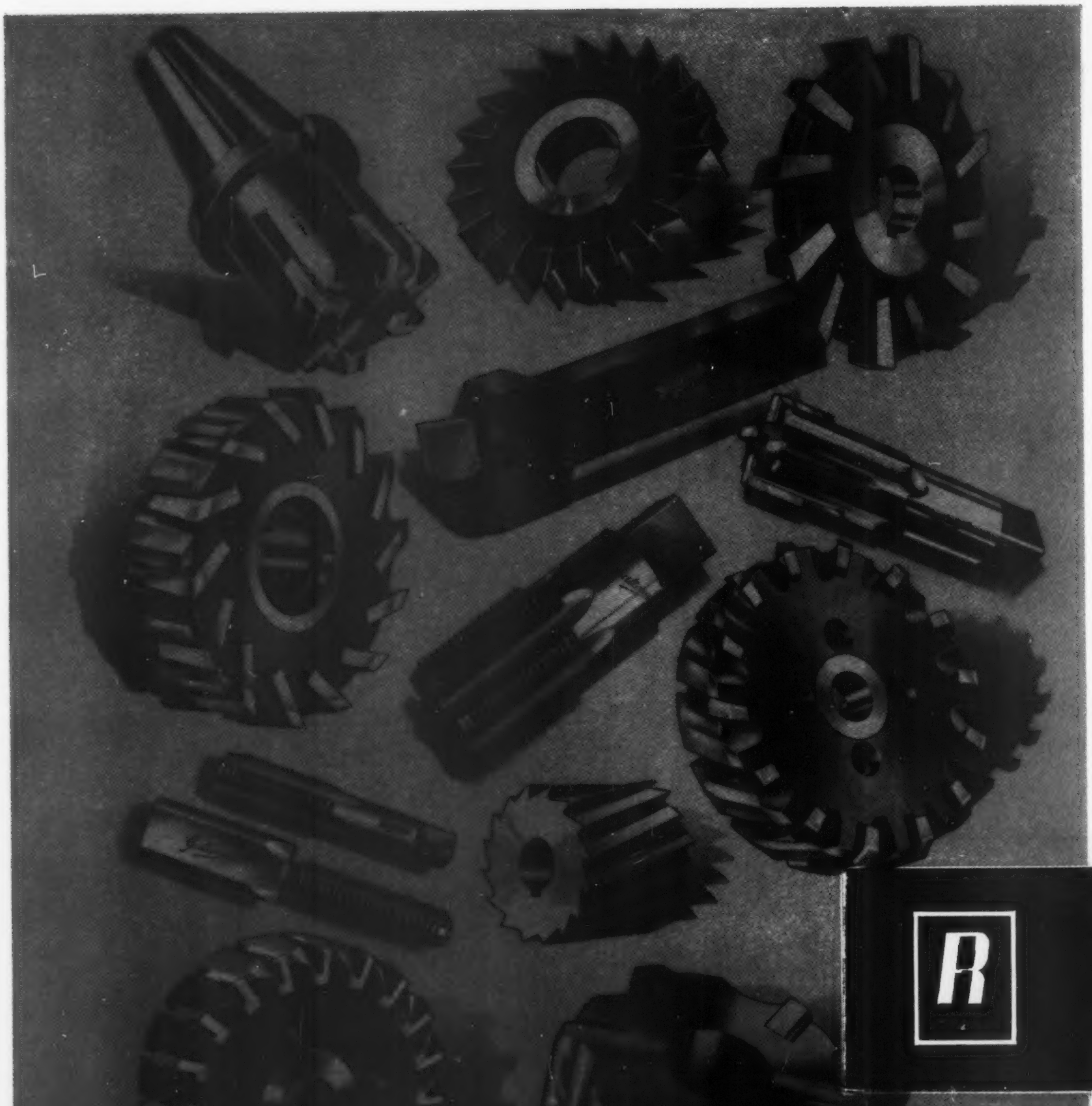


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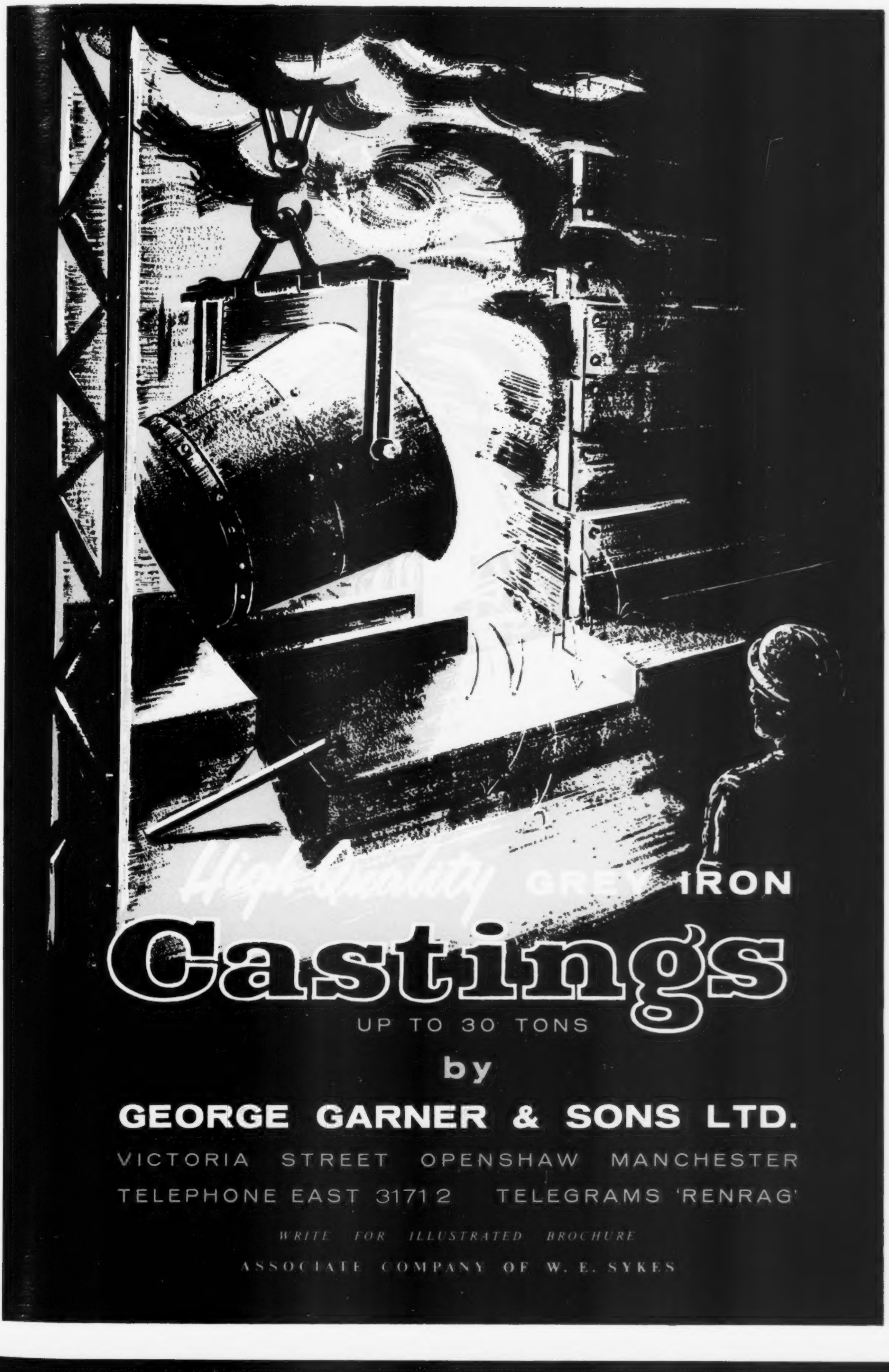
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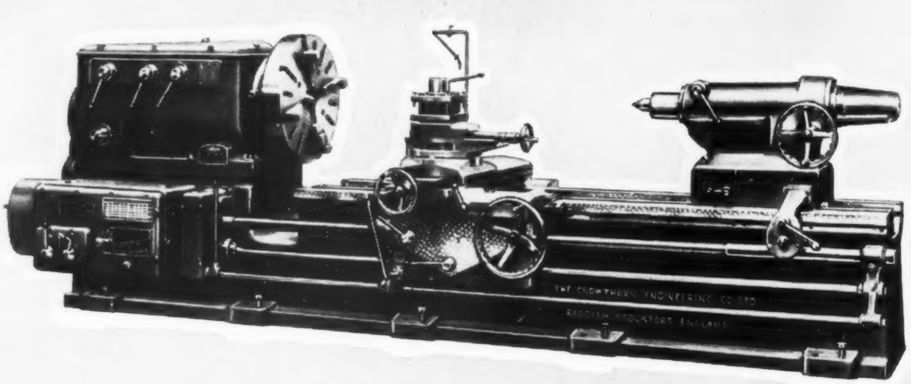

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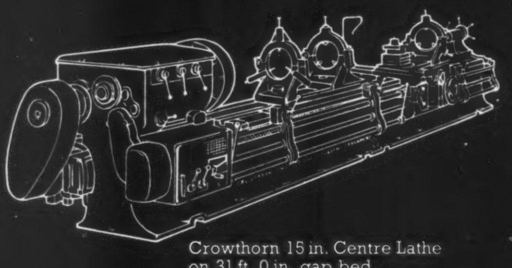

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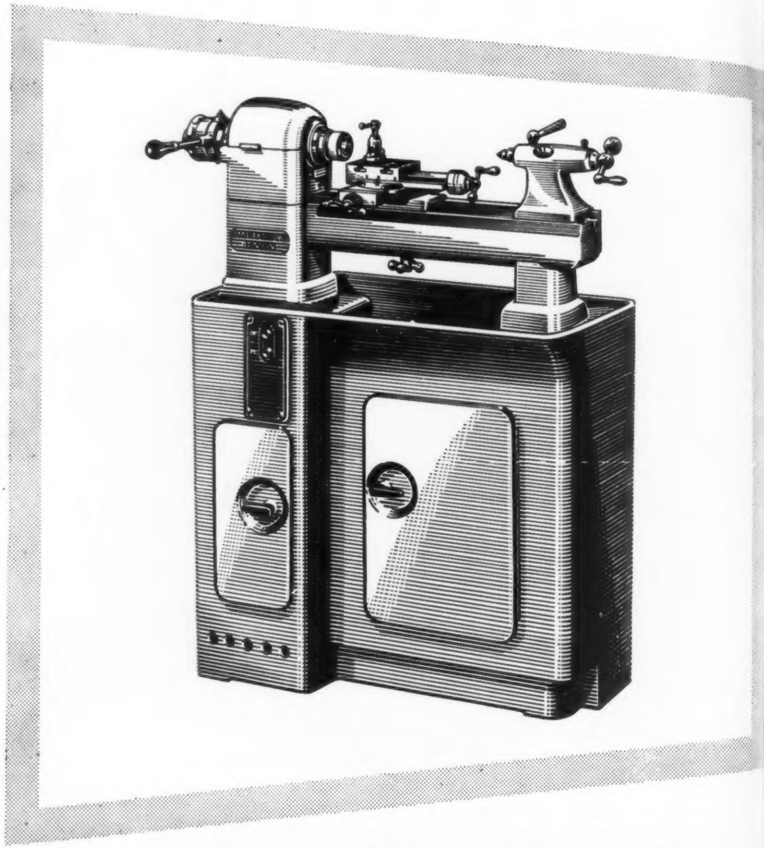

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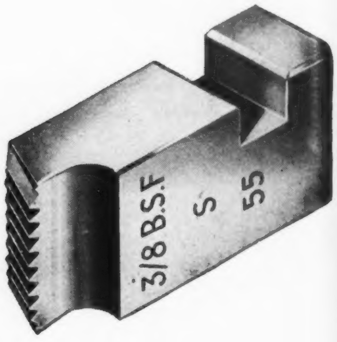

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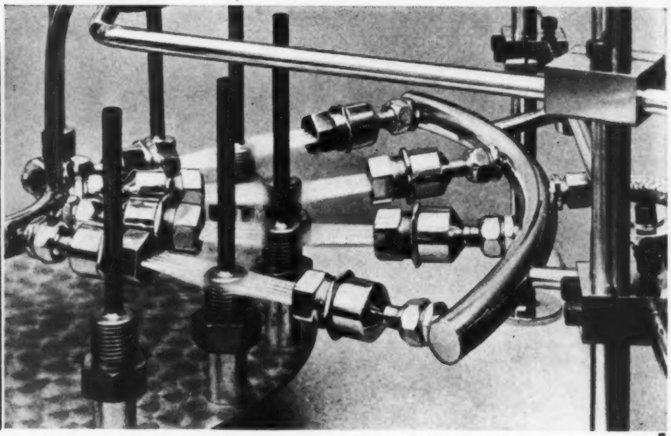

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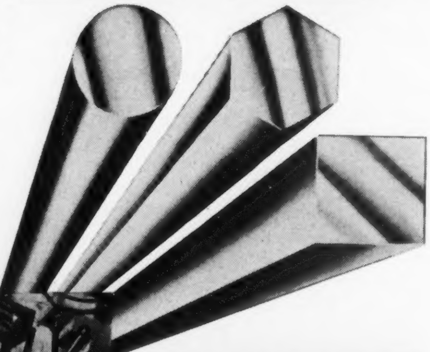

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The Production Engineer

THE JOURNAL OF THE INSTITUTION OF PRODUCTION ENGINEERS

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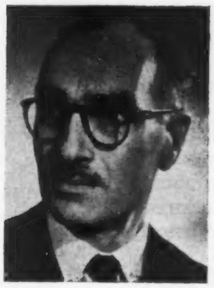
UNIVERSITIES AS FACTORIES?

by Dr. J. A. MATHESON, M.B.E.



Vice-Chancellor of
Monash University,
Melbourne.

This address was given to The Institution of Production Engineers in Australia as The 1960 James N. Kirby Paper.

The meeting, for which the arrangements were made by the Melbourne Section, was held in the Assembly Hall, Melbourne, on 25th October, 1960, and was attended by more than 400 members and guests.

THE typical factory, whether it be concerned with textiles or chemicals, furniture or motor cars, receives its raw materials at one end and discharges its finished products at the other. Within its walls are conducted the processes that are required to convert wool to cloth, ore to metal, sheet or bar stock to machines and so on, according to the nature of the particular factory. These processes differ greatly, of course, from one factory to another and at first sight have little in common: the operative in an oil refinery, for instance, who perhaps never actually sees either the crude that comes in or the petrol that goes out, probably never thinks of his work as having any similarity at all to that of a welder in a shipyard or of a mechanic in a typewriter factory. But, in fact, as soon as one begins to ignore the superficial differences between their occupations and seeks to discover the points of correspondence, one finds that there are a great many things that have to be done in all factories, whatever industry they belong to, that raise much the same problems in them all.

Indeed, it is the existence of this common ground underlying all manufacturing industry that makes The Institution of Production Engineers a possibility. If it were not so, its meetings would be very poorly attended and its Journal little read, for its members, each preoccupied with the problems of his own

industry, would have nothing to say to one another.

On the contrary, the reverse is the case. I suspect that the Institution is finding that its scope is constantly increasing. Perhaps it began by providing an opportunity for an exchange of views between men whose main interest was in metal machining, or in some other apparently closely defined operation. Before long it was found, unless I am much mistaken, that even on the strictly technical side industries do not operate in watertight subdivisions and that it was not only of general interest, but of positive direct benefit, for men engaged in one industry to study how their opposite numbers in another tackled their problems. This is even more true of technical operations, such as materials handling or quality control, which are manifestly not specific to a particular industry; and when one comes to topics such as stock control, budgetary control, factory layout, sales and marketing and 100 other subjects, it does not matter in the least whether one is making shoes, ships or sealing wax.

common ground

All this is obvious enough, and its truth is testified to by the existence of industrial consultants who apparently obtain high rewards by using the lessons they learn in one factory to eliminate the mistakes they find in another. But when I was casting about in my mind for a suitable topic on which to address you, a topic which would both fall within the broad scope of the Institution and yet be of sufficiently general interest to do honour to the name of James N. Kirby, it occurred to me that industrial production, in its broadest sense, was not unlike what goes on in a university. At least there seemed to be enough common ground to make an examination of the similarities and differences well worthwhile.

Let us begin with the similarities. Consider, for example, a factory in which steel is fabricated into building frames, cranes and bridges by welding, riveting and bolting. The whole tempo of operations is controlled by the market, and it is the business of the salesmen both to secure enough orders to keep the factory fully employed, and not to quote such delivery dates as will either infuriate the customer or the factory manager or both. If they do their work properly, then it is a straightforward job to combine the information they supply with that which comes from the drawing office so as to order the necessary raw material, the structural steel, in the right sizes and quantities. On arrival at the factory, or even in the supplier's yard, this raw material will be subjected to acceptance tests to see that it is of the correct quality and size. Any faulty material is either rejected outright or, if a remedy is possible, it is sent back to be straightened or whatever, and re-examined at a later stage.

Within the factory the accepted material begins its journey through the various processes as specified by the designers and as controlled by the production people. It is cut and machined and drilled; bits are stuck on to it and rough edges are smoothed off. At intervals it will be subjected to further tests and, if these are successfully passed, it moves on to the next stage. Eventually, after assembly, it is given its final acceptance tests and, at the very end, it is given a coat of paint and a trade mark and it goes out into the world to begin a life of useful service.

Turning now to the university and concentrating for the moment on its educational function, we see first that the tempo of operations is again dominated by demand applied this time at both ends. At the entry point there are increasing numbers of young people seeking to get in and at the delivery end are the employers anxiously looking for a supply of qualified men for their businesses. Those who seek admission must pass an acceptance test; if they succeed, all well and good; if they fail, back they go to the suppliers, to the schools, to be straightened out so that they are acceptable.

Within the university they take this and that course, in this or that laboratory, as specified by their professors. At intervals they are tested and, according to the results, are held back or moved forward. Eventually they have completed the whole course; they have been profoundly modified by this experience, stretched to their elastic limit, possibly stamped on, certainly polished and burnished, and are ready for the grand acceptance test. This passed they are given a coat of many colours and a trade mark, B.A. or B.Sc. as the case may be, and they go out into the world to begin a life of useful service.

a close parallel

So, you see, there is a very close parallel between the factory and the university; but do not start to look for your hats and coats because I have still a few remarks to make and at least one confession which I had better face up to at once. This is that I have deliberately misled you by drawing my comparison between a factory and one half of a university only, and even that half is something of a caricature and not a satisfactory portrait. It is true that what I have said corresponds quite closely with the public conception of a university, or perhaps I should say with the newspapers' conception of a university, but it is, in fact, a gross over-simplification.

The statement that a university exists for the purposes of teaching and research is a commonplace, but few of those who make the statement stop to consider all the implications. In the first place, is it true? There are institutions which are called universities, if only by themselves, in which precious little research is done and there are universities, of which the Australian National University is a familiar example, in which very little teaching is done at all and, until its union with Canberra University College, none at the undergraduate level. Evidently the word "university" has very wide application and so, for that matter, has the word "research". Indeed, it would do no harm if the word "research" was put into cold storage for a time and only brought out for use by those who are prepared to use it carefully and only then after proper definition.

It can properly be used in reference to the work of the Commonwealth Scientific and Industrial

Research Organisation. Here it clearly means discovery, whether of a fundamental or applied character, in the broad field of physical and biological science. Everyone knows too, in general terms at least, what is meant by medical research, although the methods and techniques may be obscure in the extreme. The object of research of this kind is evidently to find out about the physical world, to discover the explanation of material phenomena, and to use that knowledge for purposes which are, for the most part, beneficial to mankind.

a change of emphasis

When we move away from the sciences to the arts there is a change of emphasis. Historians and archaeologists, to be sure, must try to assemble a body of facts before they can make much progress, but the interpretation of the observed facts leads them rapidly into an intellectual activity which has little in common with scientific research. In its simplest form, science starts with an observation; one or more hypotheses are constructed by way of explanation and these are tested by experiment. In most cases, of course, the actual process is more involved and much less direct than that but in principle observation, hypothesis and experiment are the basis of scientific research.

In history the facts are often few in number, even when comparatively recent events are in question, and experiments are impossible. Imagination is the historian's most powerful weapon combined with insight into human behaviour. His conclusions can never be properly tested, in the scientific sense, but the best of them gradually come to be accepted as correct and merge into our general understanding of the development of the human race.

This is all rather different from scientific research but it is obviously much more objective than philosophy, say, or literary criticism or theology. But let us forget the word research and say that relevant creative intellectual activity is essential to a university teacher. We are now on much stronger ground and are left with the question of why it should be regarded as essential. There are two answers.

The first is that if creative intellectual activity does not occur in universities, then society would be so much the poorer. This is not to say that universities are the only places where people think but that they are among the few places where people have time to think useless thoughts, or at least thoughts that have no immediate and apparent usefulness. Indeed, there are many instances of men whose thoughts, in their own day, were regarded as not only useless but even dangerous, and who are now held in honour and esteem. That terrible fellow, Galileo, for example, had the temerity to state that heavy things fall no faster than light ones and even that the earth goes round the sun. Dangerous thoughts indeed; and Lavoisier, who showed the world the way to understand the nature of chemical reactions, went to the guillotine with the words "The Republic does not need scientists" ringing in his ears.

Not that universities are full of Galileos and Lavoisiers. Far from it. But they are full, or ought to be, of people who do not always take things at their face value and are prepared to say so. Such people are usually rather embarrassing to authority, both within and without their universities, but experience shows that they must not be suppressed if society is not to decay.

Clearly we have now identified one striking difference between a factory and a university. If the production manager were to sit in his office all day or, still worse, in his garden and think great thoughts, then it would not be long before a new production manager was in his place. But in the universities we believe it to be important and even essential that professors should be encouraged to sit and think. The only problem is to ensure that they don't just sit. Unhappily it has not so far proved possible—although this would be a proper subject for research—to discover before he is appointed whether a man is likely just to sit; but we do our best to seek out the signs of originality and creativity. Sometimes we make mistakes, perhaps more often than we should, and we are very reluctant to take remedial action when we do. The reason for this is rather subtle and will perhaps strike you as unconvincing. But it rests on the belief that, at the level we are now discussing, men are their own most severe critics and, perhaps more realistically, that a system of objective tests of creativity, if it could be devised, would be bound to defeat itself; you remember the goose and the golden eggs.

research and teaching

I said earlier that universities exist both for research — the discovery of new knowledge and the re-evaluation of old — and for teaching — the handing on of knowledge to the young, but opinions differ widely on the relative importance of these two functions. Flexner, who took a close look at American and European universities in the 30's, came to the conclusion that "the university professor has an entirely objective responsibility — a responsibility to learning, to his subject, and not a psychological or parental responsibility for his students". On the other hand Cardinal Newman proclaimed, in effect, that "the principal aim of the university is to train people for society". The practice of most universities in the British Commonwealth lies between these two extremes although, it must be admitted, senior staff are most often picked for their capacity for original research, which is fairly easy to identify, than for their ability to train young people which is usually, if sometimes erroneously, taken for granted.

This brings me on to the second reason for regarding individual creativity as important. Teaching at university level is, or ought to be, a very different operation from teaching at elementary level. There is no question of hammering the basic facts of reading and arithmetic into reluctant heads, but rather the creation of circumstances in which the most brilliant minds of the current generation of young people can come to full maturity. In this process the teaching of facts is of diminishing importance and, as the

student gets older, gives way to the presentation of ideas about the future of knowledge and wisdom. This cannot be done by pedestrians who tread only along the paths that have been blazed by others.

The educational responsibilities of universities, then, can only be fully discharged if the best students are taken to the stage when they can think, for themselves, critically and creatively about their subjects, so that with experience they can become leaders in the professions, in industry or in government as the case may be. Do not imagine, though, that I am claiming that the universities are the only places from which leaders emerge. The University of Oxford was once described as providing an opportunity for self-education in the most agreeable circumstances, and it is easy to find many examples of men who have educated themselves in circumstances of difficulty and adversity that were far from agreeable. They were none the worse for that, perhaps, and there will always be such; but the trend of the times is for a continually increasing proportion of the population to enter the universities, which have thus the inescapable responsibility of seeing to it that the best brains are fully stretched.

the Vice-Chancellor's dilemma

But there are obviously much larger numbers of young people, of great ability and capacity, who are certainly going to do a useful job in life without reaching the heights of intellectual achievement. Very often they go further than their more brilliant colleagues because of their personal charm, or their determination or even their capacity for sheer hard work. How should they be educated? Or the larger numbers still of quite ordinary people, pass degree men if you like, who go to universities in the belief that they can thereby be fitted for a career which demands at least a certain minimum level of professional competence? Here you see the dilemma of the Vice-Chancellor who has, in this respect at least, a more complex job than a factory manager's. If a factory is to produce high quality cars, for example, or precision machine tools it is set up in a different way from that which would be appropriate for the mass production of popular cars or the manufacture of cheap toys. Even though the raw material, steel and cast iron and so on, may be much the same, the techniques are not and, even more important, the underlying philosophy is totally different. In the one case the objective is perfection, to be obtained by individual craftsmanship and the possibility of adjustment and fitting; in the other the objective is a large output of products of adequate quality, virtually identical and built up of interchangeable components.

Not only does the factory manager have a clear objective; he can and does choose his raw material with an eye to the finished product and apply to it acceptance tests which, if skilfully devised and executed, will ensure a very small proportion of rejects. The university is in a much less well-defined situation. We have seen that it is under compulsion to produce both racehorses and carthorses, or Field-Marshals and Captains (if you prefer that metaphor); in addition, it is presented with raw material of very variable quality while it does not possess acceptance tests of very high discriminatory power. It is true that we require our students to pass the matriculation examination, but experience shows that this is a rather poor means of separating sheep from goats. Unfortunately, there is no agreement on how it can be improved, although it is realised that the results of an examination of this type are influenced not only by the candidate's knowledge and, even less precisely, by his capacity, but also by his school and the sort of teaching he has received, by his family background and other environmental influences, and by the state of his nerves and digestion when he sits down to write. From this standpoint the surprising thing is not that the failure rate in universities is as high as it is, but that it is so low.

What is it that we are trying to discover by means of this examination? Let us be clear first that we are not trying to discover whether the candidate will make a good engineer, school teacher or businessman, but rather whether he will be able to enter these and other professions by the particular route we are considering — the university route. It is true that some professions, notably medicine, have now decided that a university degree is an essential prerequisite, but this does not disturb my argument that the purpose of the admission test is to see whether the candidate will make a success of being an undergraduate and this turns on the other qualities than the mere possession of book learning. We need to know whether the student can think for himself, work by himself, adjust himself to a new and much less externally imposed set of disciplines, apportion his time properly between work and leisure, perhaps adapt himself to co-educational society, certainly begin to get used to the decision-making circumstances of adult life rather than the decision-accepting circumstances of childhood. And all this at a time when he is undergoing the metamorphosis from boy to man.

the problem of prediction

It is, without doubt, very difficult indeed to devise predictive tests to throw light on all these matters and it would be still more difficult to persuade parents that they were reliable even if we could devise them. But do not let us be surprised if we don't do too well by using as a yardstick the marks a boy gets in an examination of limited scope on work that has been presented to him by school rather than by university methods; it is not really much help to know that he got 50 rather than 49 marks in such a test.

For my part, while realising the disadvantages, the waste of effort and the disappointments, I prefer the Australian practice of admitting to universities more students than are likely to succeed, to the British way of trying to restrict entry to those who are certain to succeed. I would prefer to say to a boy — "in my opinion you will have a very hard struggle but, if you wish, you may have a try" than — "you may not even have a try". But having said that, I must

also say that it is then up to the universities to give him adequate opportunities, up to the State to give the universities enough staff and buildings to ensure this, and up to the society to accept that if a boy comes unstuck in his first year it is a pity, but it is not the end of the world or even of his career.

So much for admission — what is to happen to our student when he actually becomes an undergraduate? Here again the production manager has the advantage over the professor, because he has a clear picture of the product he is supposed to be making, and it soon becomes obvious, in spite of the publicity boys, if that product is not good value for money. But even in the case of a reasonably well-defined profession like medicine, where the only requirement is the straightforward one that the graduate doctor should be able to heal the sick and keep the healthy from falling sick, there are plenty of opinions as to the right way to arrange the training schedule. Shall there be more or less fundamental science? And what science? Mathematics? Probably not: Biochemistry? Certainly: Physics, Botany, Zoology, Chemistry, Entomology? All of these certainly have some claim on the medical student's time, but how much? And we have still not reached the subjects like Anatomy, Physiology, and Pathology, that must obviously play a major part in the course.

A similar discussion can be conducted about all the professional courses; the only conclusion that emerges, and it is a qualitative rather than a quantitative one, is that the better the student the more he should strive to master the fundamental sciences and the less time he need spend on application. The reason for this is quite simply that the better students are the ones that are likely to become intellectual leaders and to make advances in knowledge and techniques, and these increasingly depend on advances in basic science.

Perhaps I have said enough to make it clear that a professor's task is by no means straightforward, even when vocational courses are in question. But a very great number of students go to universities without having a precise vocation in mind or, having chosen one vocation, find that events sweep them into another; engineers, for example, occasionally become Vice-Chancellors and often become managers at various levels of industry. There are, in fact, so many examples of men who have switched from one branch of technology to another, from pure to applied science, even from arts to industry, that one begins to wonder whether it is not more the rule than the exception. I must put this topic on the list of future research projects for Monash University. Without waiting for the results of this enquiry one can be sure that in our society the trend is for men, especially the successful ones, to have to discharge responsibilities that are increasingly general in character as they get older. School teachers become headmasters and possibly directors of education; accountants join boards of directors; lawyers become judges and practically any educated man can become a politician. As their duties widen these men can obviously no longer rely on the details of what they were taught at their university: they increasingly find that they are falling back on general principles, on habits of critical thought that they developed as young men, and on such talents for human relations as they may possess. Clearly the education of such men should not be narrowly conceived and this brings me to the educational dilemma of the professor: this is, that for all sorts of reasons undergraduates should be exposed to a wide range of disciplines, which certainly straddle the gap between the two cultures, but that the continual advance of knowledge, especially in the sciences, seems to demand increased specialisation.

This is not the place to discuss all the implications of this dilemma but I might just comment, in passing, that experience in Russia, in America and on the Continent of Europe suggests that we are trying to get too much into our three or four-year undergraduate courses and that we must develop postgraduate courses for the brighter students. If it became the general practice for these men to stay on at their own university or, better still, move to another one for this purpose, then the first-degree work could be made broader in character and perhaps a little les arduous in standard and, even more important, the schools could return to their proper role of giving a general education.

a change in attitude

However, such a fundamental change is not likely to come about in the near future, because it implies a change in the attitude of our society to higher education. This has occurred in America because of the impact of competitive capitalist industry on an egalitarian school system; it has occurred in Russia, as I see it, because Communist ideology and the demands of successive five-year plans rather suprisingly coincided with the old aristocratic conception of the professions which survived the Russian as it did the French Revolution. It remains to be seen whether the British communities will eventually come round to the same system.

In the meantime the British professor will continue, as he has done for generations, to exhaust his ingenuity in trying to get a quart into a pint pot. But he will also continue to exhaust himself in trying to do four or five jobs at once. Now that I am no longer one of them, I am free to say that society makes heavy claims on its professors. In this respect it seems to me that industry has something to teach the universities in the matter of devolution and delegation of responsibility. I was never a factory or departmental manager in industry, but when I saw my friends who were in this position going off to their golf or sailing at the weekend, or digging their gardens or even sitting in them, while I remained at my desk, I was tempted to think that they were more fortunate or more intelligent than I, or both.

Consider, for a moment, what you expect of a professor in these days. It is taken for granted that he is an authority on his subject and has contributed and will continue to contribute, original ideas to its development. He is expected to lay down the policy of the courses for which he is responsible and to give an appreciable proportion of the lectures himself. In

Mr. J. M. Steer, then President of the Australian Council, presenting the James N. Kirby Medal to Dr. Matheson after he had delivered his Paper.

my observation the best professors, those whose students got most out of their studies and remember their student days with affection and gratitude, give a good deal of attention to the development of their students, both intellectually and in a wider sense. They are expected to administer their departments, in the sense of recruiting and promoting academic and technical staffs, preparing budgets, applying for research scholarships and 100 other tasks, none very recondite or time-consuming in itself, but contributing to a formidable total. They are expected to play their part in university government, at Faculty and Professorial Board level certainly, and to some extent at Council level as well. They are certain to be asked for expert advice as consultants, if they are skilled in appropriate fields, or invited to join advisory committees. They are expected to play some part in public affairs; to address professional bodies and serve on their committees; to speak at school speech days, on radio and television, and to be ready to review books, write articles and comment on the news whenever the Press calls on them.

A friend of mine, just elected to his first Chair, was advised by a senior colleague to decide at the outset which of his duties he was going to neglect. Unhappily, it is scholarship that is the easiest to neglect, for administration can seldom wait.

Can the universities learn any lessons from industry about all this? I think they can but I also think that it would be dangerous to follow the industrial pattern too closely. But before explaining in detail what I mean let me first say, with all emphasis, that universities have got into the habit of running with too small an establishment of clerical and administrative help. This could easily be corrected, at some expense, and governing bodies would be well advised to see to it that they do not prevent their professors from doing the jobs for which they were appointed by denying them proper assistance at a comparatively humble level.

Industry, in my observation, does not usually make this mistake, for it recognises that it is most economical to ensure that all essential work is carried out by people on an appropriate salary. Managing directors do not do their own filing.

the organisation chart

But the organisation chart, with its chains of command and clean devolution of responsibility, should be applied to universities with great caution. At least there should be various cross-connections and short-circuits which, although highly inappropriate in a factory, are essential to the health of a community of scholars, each chosen for his originality and individuality. It is for this reason that the concept of permanent Deans of Faculties finds so little favour in British and Australian universities; individual professors, by tradition and often by statute, are responsible for the subject of their Chairs and they do not see why a Dean should stand between them and ultimate authority. I do not for my part altogether share this uneasiness; I see clear need for an individual whose main responsibility is for a faculty, a group of related subjects, and who will cherish the development of that faculty just as each professor cherishes the development of his department. In theory the system of electing Deans in rotation from the professors of the faculty meets the need but, having been one, I am quite clear that the Dean who must also run a department during his term of office carries an intolerable burden in a university of any size.

Then take Deans of Students. These gentlemen flourish in the United States, where they are responsible for the discipline and for all extra-curricular activities of the students. In theory this is a fine idea, for it relieves the professors of a large chunk of what some find an onerous duty. No doubt the system works well when the Dean of Students is a fine and wise man. But it has two serious dangers: it relieves professors of, or even takes out of their hands, what I consider to be an essential part of their work, namely the direct personal supervision of their students' development; and it may channel the students' appeals for help, moral, psychological or physical, into a single route. There is something to be said for having many points of appeal which the student may choose as he will — or choose to ignore.

In this context the Vice-Chancellor's dilemma is in choosing how much organisation to lay on. Too little, and his professors are overworked and frustrated and the university is inefficient in the sense that ideas are not smoothly translated into action. Too much, and the university becomes a factory, with each operative obediently carrying out his allotted task on the production line.

Sir Eric Ashby, formerly Vice-Chancellor of Queen's University, Belfast, once said that you could distinguish a good university from a bad because in

(*concluded on page* 138)

MODERN TRENDS IN THE MANIPULATION OF METALS

by Dr. D. F. GALLOWAY, Wh.Sch., M.I.Mech.E., M.I.Prod.E.

Director,
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This Paper was presented as the opening address to the National Conference of The Institution of Production Engineers at Brighton in October, 1960.

Papers presented in other Sessions of the Conference will appear in subsequent issues of "The Production Engineer".

IN British industry today there is a great need for a wider exchange of ideas and experience among firms already using metal forming techniques. There is an even greater need for effective dissemination of the potentialities of these techniques to hundreds of firms where expensive and very wasteful *metal cutting* processes could easily be replaced by extrusion and other *metal forming* processes which would give immense savings in raw materials and labour, and would benefit producers and consumers alike.

Recent visits to research stations and factories in several European countries and Russia have revealed a growing emphasis on the replacement of metal cutting by metal forming. If I may borrow a phrase from my colleague, Mr. Howard, the emphasis is on "moving" metal instead of "removing" metal. In metal cutting operations the finished component weighs on average only about 60% of the bought-in material, the remaining 40% being removed by expensive machining operations and ending up as chips or swarf with its value reduced to about 5% of the original in the case of steel. The elimination of such waste is a matter of international concern, and O.E.E.C. is currently considering co-operative research programmes developed and endorsed by most of the industrial countries and designed to deal with this specific problem of the substitution of metal forming for metal cutting.

Meanwhile in Russia, for example, TSNITMASH, one of their oldest research stations with a staff of over 4,000, is devoting considerable attention to metal forming techniques and equipment, and they now have a separate research station, ENIKMASH, with

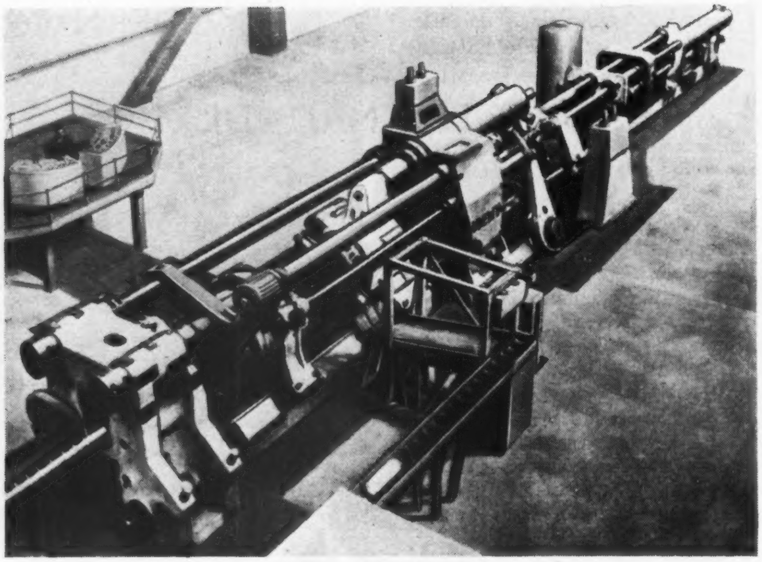


Fig. 1(a). 3000 ton horizontal extrusion press.

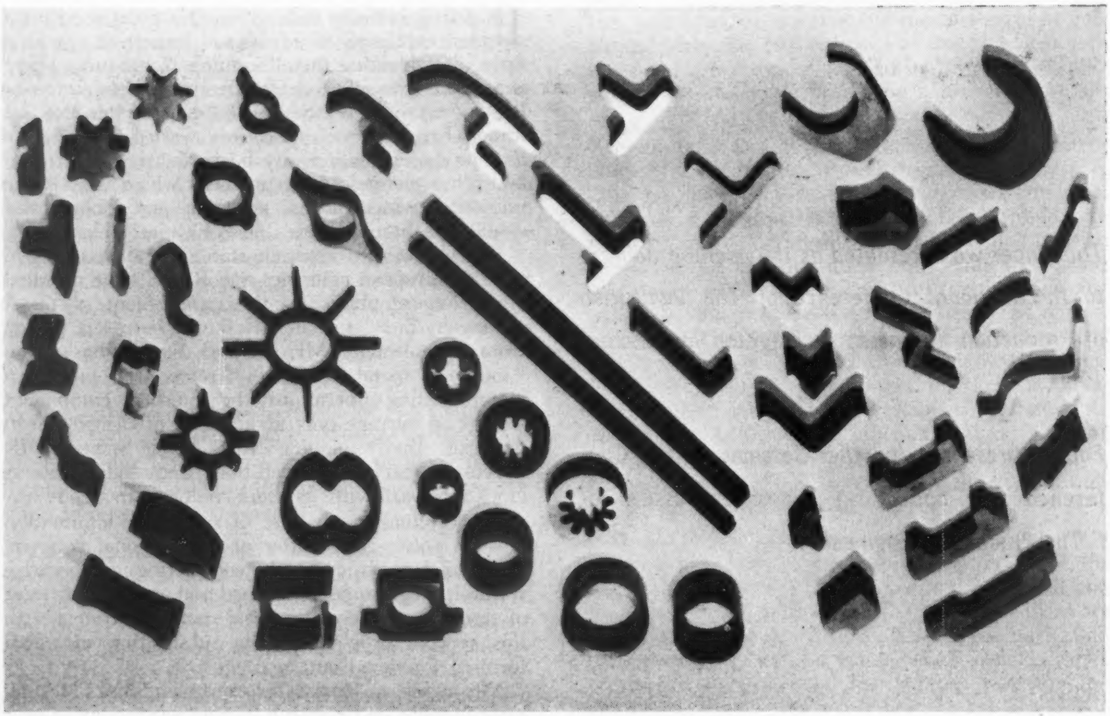


Fig. 1(b). Typical extruded sections.

Fig. 1. Hot extrusion of steel by the Ugine-Sejournet process.

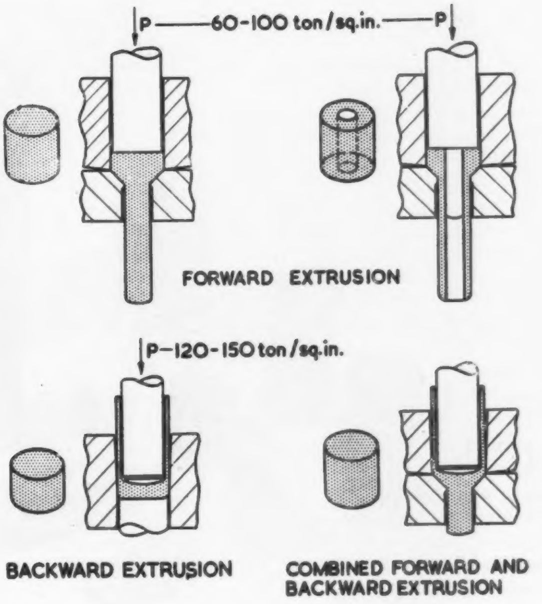


Fig. 2. Basic operations for the cold extrusion of steel.

a staff of about 2,000 solely engaged on presswork-ing and forging research. Some of the recent developments include extrusion under conditions of high hydrostatic pressures of 10,000 atmospheres, sheathed extrusion at speeds of 1,000 ft. per min., and in their large scale work they have developed a 70,000 ton press with 100 ft. columns for aircraft components.

In Czechoslovakia, some excellent research is being carried out at the Metal Forming Research Institute near Brno, and the significance attached to this by the Czechoslovakian Government can be judged from the fact that whereas the Government assistance in metal cutting research is 10% of the total cost, the assistance for metal forming research is 70%.

Recently I was looking at metal forming developments in Germany, and apart from developments of individual techniques such as deep drawing without a blank holder, I was particularly impressed with the extent to which they are automating press lines and linking them through to associated activities such as electric welding to give complete pressed and welded assemblies.

However, to turn to the particular subjects of this Conference, I have been asked to say a few words on recent developments and future prospects of extrusion processes, forging processes, rolling and sheet metal forming.

extrusion techniques

hot section extrusion

Hot extrusion is now a well-established process and extruded sections in non-ferrous materials such as aluminium, copper and brass are in large scale use in industry and applications are steadily increasing. For example, extruded aluminium section is now being developed in the U.S.A. for the production of car bumpers.

Hot extrusion of steel sections by the Ugine-Sejournet process, which involves the use of molten glass lubricant, is steadily gaining ground and may increasingly replace rolling and drawing operations when precise and intricate sections are required. A 3,000 ton horizontal extrusion press and typical extruded steel sections are shown in Fig. 1.

cold extrusion

Cold extrusion, or impact extrusion as it is sometimes called, was first applied to soft ductile materials such as lead and tin, and then to aluminium and other non-ferrous materials. The extrusion of steel was first carried out over 30 years ago in Germany and the process was rapidly developed by the Germans immediately prior to and during the last War for the production of certain types of ammunition.

After the War, the process was further developed in America and, more recently, by various other countries including Great Britain. Commercial applications of cold extrusion of steel are steadily increasing, although perhaps not quite so rapidly as was expected 10 years ago.

Whether the material is deformed by forward extrusion, backward extrusion, or a combination of forward and backward extrusion (Fig. 2), a great variety of component shapes is possible, as shown in Fig. 3. The work hardening of the material that occurs during the operation has a significant effect upon the mechanical properties (Fig. 4). In low carbon steel, for example, a component having a tensile strength of about 20 tons per sq. in. can, after extrusion, have strengths of the order of 40 - 50 tons per sq. in., depending on the amount of deformation involved. This means that it may be possible to specify a cheaper material than would be required for other methods of manufacture. The improvement in tensile strength and hardness is accompanied, of course, by a decrease in ductility but in many applications this is of little consequence. The surface condition of extruded components is excellent and, as shown

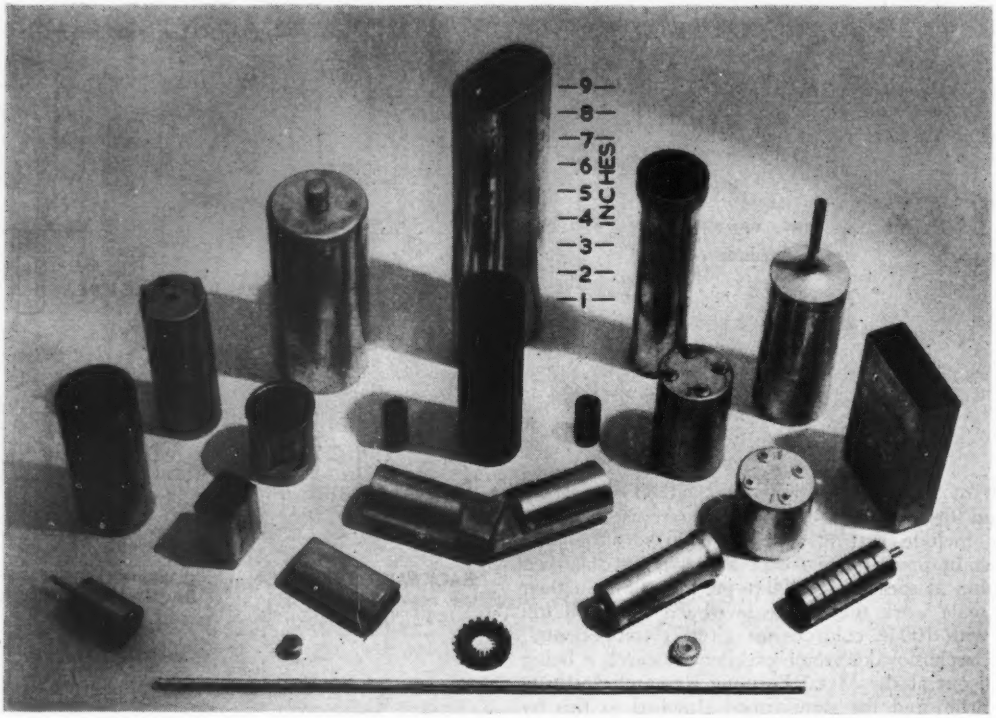
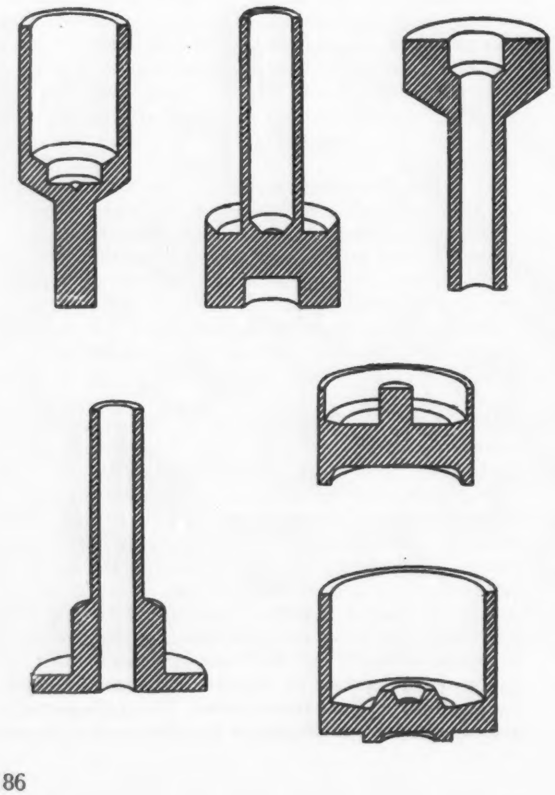


Fig. 3(a). Typical component shapes suitable for cold extrusion.



in Fig. 5, this is often superior to the finish achieved by machining operations. Dimensional accuracy is also very good; for example, with a backward extruded component it is possible to produce a bore of 1 in. with a tolerance of $\pm$ 0.001 in.

Cold extrusion of steel is the most severe of all metal forming processes, some indication of the punch pressures for various materials being given in Fig. 6. In view of the severity of the operation and relative shortage of reliable technical information, it is not surprising that industrial applications have proceeded cautiously. Although more analytical work has been carried out on extrusion than on other metal forming processes, mathematical theories are not yet developed far enough to deal with all the complexities of the operation but much practical research has been carried out abroad and in this country by N.E.L. and PERA in order to provide information on various process variables, and hence deduce optimum conditions for producing specific types of extrusion. At the same time, work has proceeded on the development of improved work materials and tool materials, heat treatment procedures and lubrication techniques.

Fig. 3(b) (left). Typical component shapes suitable for cold extrusion.

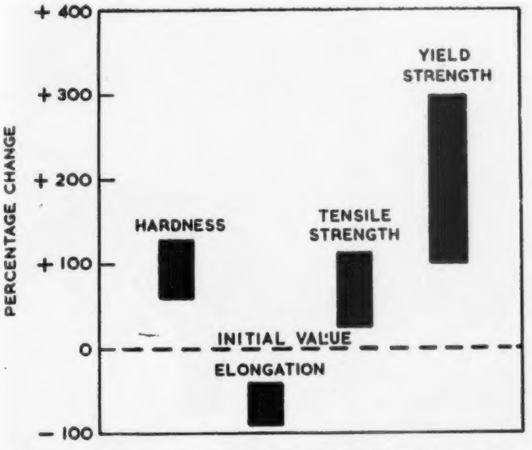


Fig. 4. Approximate changes in mechanical properties of steel due to cold extrusion.

Developments have also been made in the design of suitable presses for cold extrusion. An example of this is a special double-action hydraulic extrusion press (Fig. 7) which has been designed in Britain by the Bliss Company in co-operation with PERA. The design of this machine incorporates many of the lessons learned in carrying out extrusion research over the past 10 years, and it is thought that the press will offer significant advantages over existing types of machine.

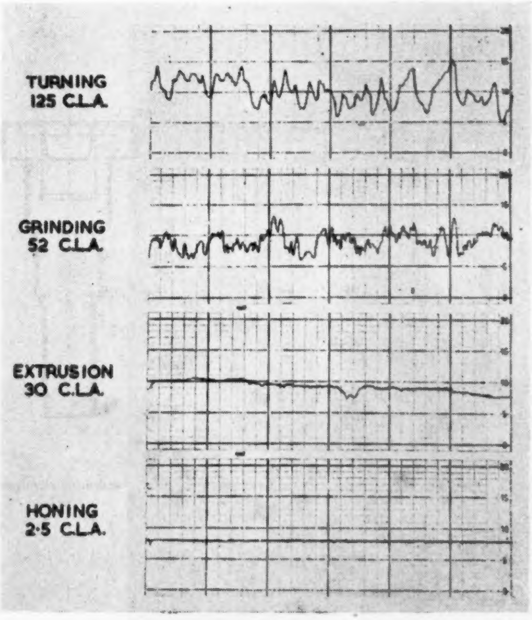


Fig. 5. Comparative surface texture resulting from cold extrusion and machining operations.

One aspect of the cold extrusion process which is receiving particular attention at the moment is the production of slugs or billets. One of the most desirable ways of producing billets is by shearing from bar; this avoids waste and high production rates are possible, but unfortunately the rough sheared surface that is usually obtained with the soft material required for extrusion has to be removed or smoothed in some way, often by a separate coining operation. Because of this, attention is now being given in various countries to the development of improved shearing processes and useful progress has already been made. As an alternative to shearing, billets are sometimes sawn from bar or parted in a lathe. In each of the cases, however, wastage occurs and the operation is slow. Clearly, much further development is needed to provide an economic method of producing billets of the desired quality.

Although a good deal of research and development work has already been carried out, it is still extremely difficult to predict with any certainty the extrusion conditions for a new component or component shape, and for this reason each new shape usually has to be developed by practical trial in order to deduce the best tool shapes and operating conditions. During the past two or three years, PERA has been augmenting cold extrusion research with practical tool development work to establish techniques for individual components, an interesting example of this being the development of extrusion techniques for the production of special atomic reactor fuel cans for the United Kingdom Atomic Energy Authority (Fig. 8).

In the future it is likely that more and more applications will be found for cold extrusion, particularly in the mass producing industries such as, for example,

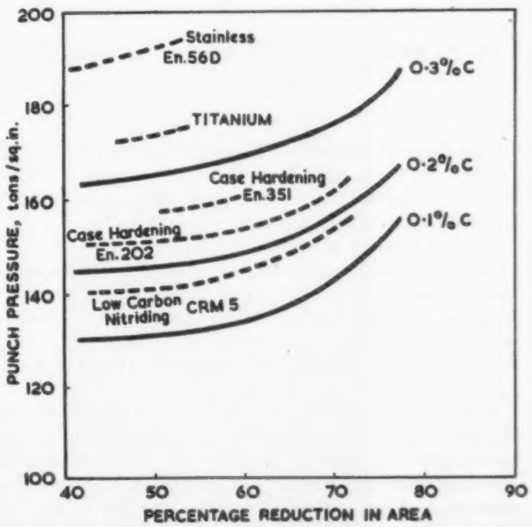


Fig. 6. Effect of percentage reduction in area on punch pressure when cold extruding titanium and various steels.

Fig. 7. 300 ton double-action hydraulic extrusion press.

Fig. 8. View of press and tooling for forward extrusion of aluminium fuel can for atomic reactor.

the motor car industry. As research proceeds and as better materials, tool steels and cemented carbides become available the process will become applicable to more complex shapes and materials.

An interesting outcome of the recent application of cold extrusion to steel parts that were previously hot forged has been the development of improved forging techniques that can compete more closely with cold extrusion, because of the greater accuracy and smaller machining allowances required. A typical example of this is shown in Fig. 9.

Perhaps the most significant point to emerge during the past two to three years is that components should be designed in the first instance for cold extrusion if the maximum possible benefit is to be gained from the operation. A good example of this is given in Fig. 10, where a component as originally designed for production by machining (a) is compared with the same part re-designed to facilitate extrusion (b).

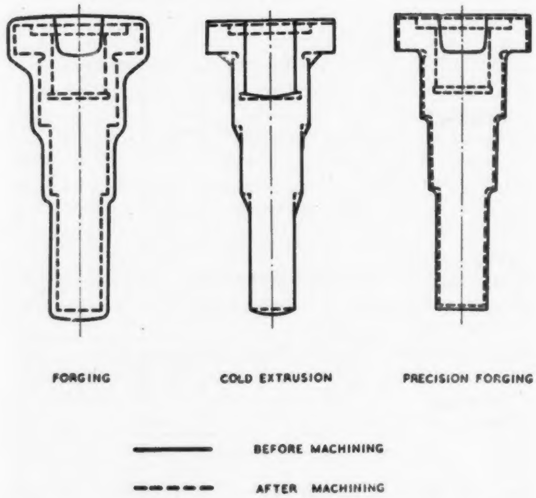


Fig. 9. Comparative profiles of component showing material utilisation when produced by various methods.

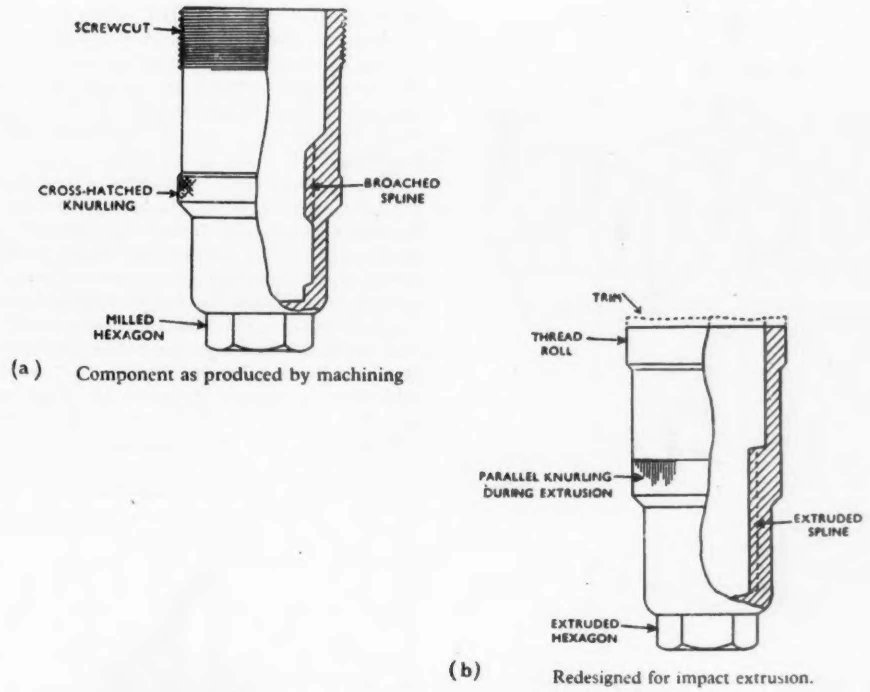


Fig. 10. Design of component for extrusion.

Fig. 11. Typical induction furnace installation for heating of forging billets.

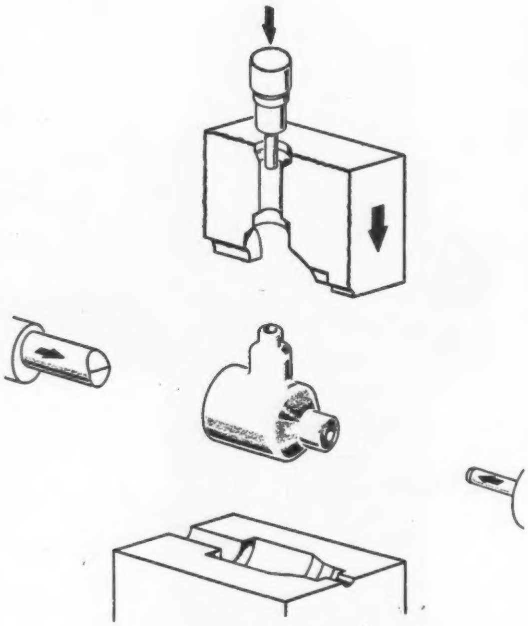


Fig. 12. Principle of cored forging process.

precision forging

improvements and developments to existing techniques and equipment

Many improvements have taken place in recent years in hot forging operations with a view to obtaining improved precision and hence the need for less machining after forging.

Accurate control over heating for forging is essential for the production of high quality work. In the main, furnaces of the oil or gas fired type are used but in recent years there has been a trend towards the use of electric heating, either by resistance or induction methods, a typical installation of induction heating for forging being as shown in Fig. 11. In addition to their more accurate control, electric furnaces have an advantage in that the atmosphere can be readily controlled and thus reduce scaling; with suitable automatic control equipment, they can also be used in automated forging lines.

An interesting development reported recently is the use of cast molybdenum dies, which permit higher forging temperatures and thus enable more work to be carried out in the dies. It is likely, however, that this development may be somewhat expensive and a better proposition would appear to be the use of heated forging dies which have recently been investigated in the U.S.A. In the investigations reported, Inconel dies have been heated by tubular electric resistance heaters to a temperature of 800°C, thus considerably reducing the cooling effect when the billet or bar is placed in the dies. This has permitted forgings of greater precision to be produced and has enabled thinner metal sections to be achieved with fewer operations. The lubricant that has been used for this work contains 67% potassium iodide, and 33% flake graphite.

The decision as to whether a given component is forged under a drop stamp or hammer is often dictated by necessity rather than choice, although it would appear that presses are being increasingly preferred to drop stamps. There are arguments for and against presses and hammers, although with presses production rates can usually be significantly increased and working conditions are better. Automatic control can also be applied to presses, but would be very difficult to apply to hammers or drop stamps. Frequently, several sets of dies are used in the one press and forming rolls are often employed to preform the material prior to press forging. The forming roll has the additional advantage of removing most of any

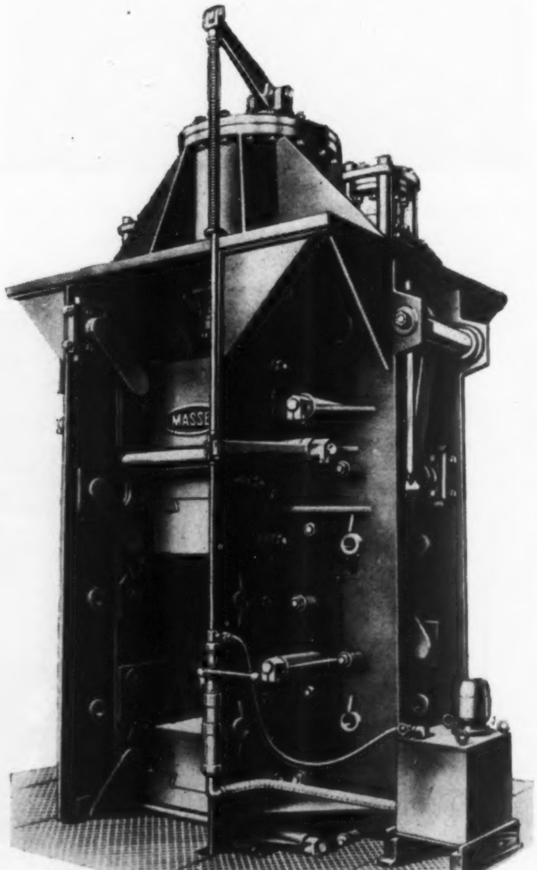


Fig. 13. Counterblow forging hammer.

scale that may be present, so that the actual forming operation is carried out in comparatively clean conditions and as a result more precise work is usually possible. Even so, it is interesting to note that after press forging, a final impression is still frequently given by drop stamping.

Other precision forging processes which have been steadily developed over the years include cored forging (Fig. 12) as carried out in the hot brass pressings industry, and horizontal upset forging, usually carried out in multi-stage machines. Upset forging is usually a very economic operation and, for example, a recent installation in Germany is reported to be upset forging motor car torsion bars 10 times faster than the previous method of production. This installation is well mechanised and includes induction heating plant as well as conveyors.

new techniques

The counterblow hammer was originally developed in Germany and there are signs that this type of equipment may be increasingly used in the future.

This type of hammer (Fig. 13) overcomes some of the factors that limit the power of conventional drop hammers, where up to 30% of the energy may be lost through the anvil into the foundation. The heavier the anvil the less energy lost but this, of course, merely increases the size and cost of the installation. In the counterblow hammer the large inertia mass needed in the anvil block is eliminated. The two rams, synchronised by coupling systems, meet at the centre of their combined travel, where the workpiece is held. The rams are usually the same weight and move at the same speed, and the force of the blow transmitted to the foundations is negligable.

A type of counterblow hammer forging process, known as "impacting", was reported in the U.S.A. several years ago. Essentially, impacting is forging carried out in mid-air as shown schematically in Fig. 14. Two opposed horizontal rams, operated by compressed air or steam, carry the forging dies. Their strokes are timed by electronic controls so that the two rams always come together in the same plane of impact. For forging, material is suspended between the dies, usually by an elaborate system of transfer fingers, and struck on both sides simultaneously. Rapid production rates are possible with this equipment and automatically controlled installations can be provided.

Another precision forming process which has been developed during recent years is known as rotary forging or the G.F.M. process, shown in principle in Fig. 15. In the basic machine, three, four or more hammers converge radially on the workpiece somewhat as they do in a rotary swaging machine. Equally spaced around the workpiece, they all strike it at the same time. The outer shape of the forging comes from the shape and setting of the hammers. The workpiece is rotated to produce round shapes, but other cross-sections may be produced without rotating the workpiece. Hollow components can be forged around a suitably shaped mandrel, as shown in Fig. 16. Machines for forging by this process can

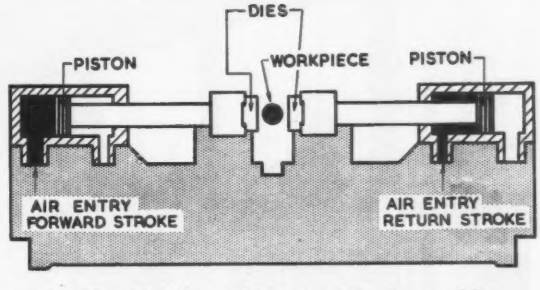


Fig. 14. Principle of "impactor" forging machine.

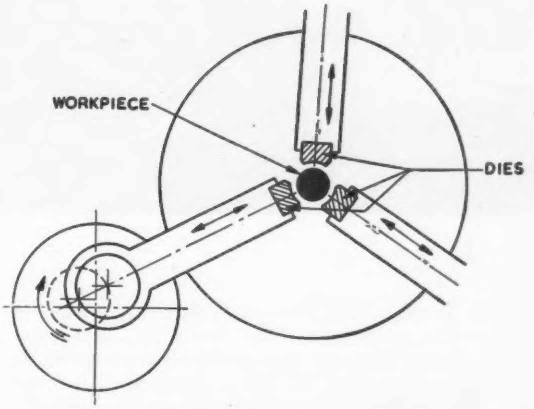


Fig. 15. Principle of rotary precision forging.

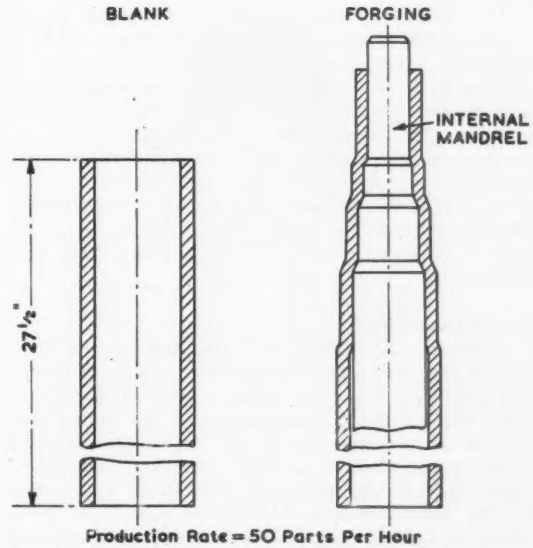


Fig. 16. Typical component produced by precision rotary forging.

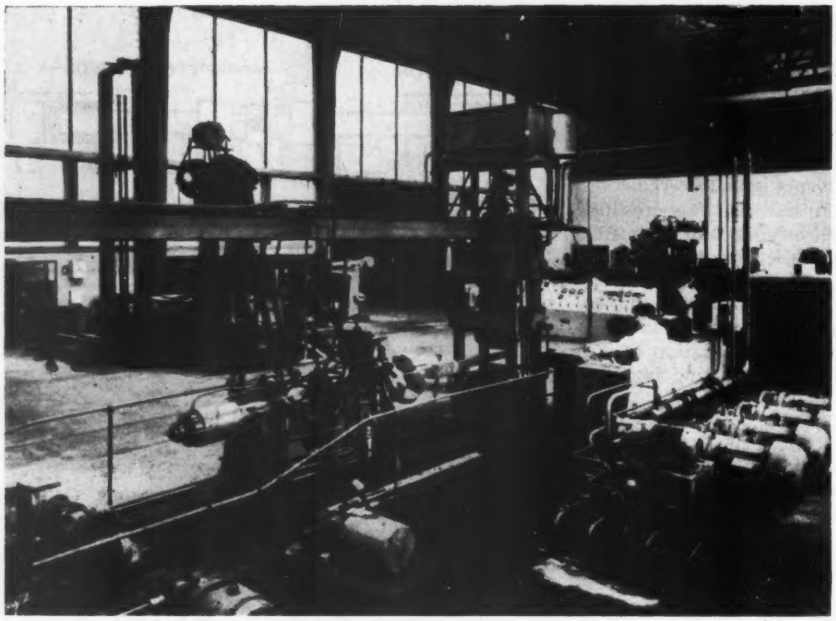


Fig. 17. Linked forging press and manipulator developed by B.I.S.R.A.

provide forces of 220 tons and operate at speeds of 600 strokes per minute. The two main advantages of the process are high precision and high speed. It has been stated that in regular production, forgings can be finished to tolerances of $\pm$ 0.012 in. externally and $\pm$ 0.004 in. internally.

A further development which can influence most of the known forging processes is the increasing development of control mechanisms. A good example of this is the automatic forging machine developed at the Sheffield Laboratories of the British Iron and Steel Research Association (Fig. 17). In this system of forging with an interlocked press and manipulator, very precise forging can be accomplished in a small fraction of the time taken conventionally.

Although the forging industry is a very old one, many developments have taken place in recent years with a view to obtaining forgings of improved precision and it would appear that these developments will, if anything, be accelerated during the next decade.

precision rolling

Although the rolling of screw threads was first carried out over a century ago, the quality of thread was poor and it is only during comparatively recent years that engineers have recognised the rolling process as an effective means of displacing metal to produce components of high precision and finish. Screw threads still represent the largest application for the rolling process. Millions of parts have been produced annually by the fastener industry alone, and in some firms as many as 10 hopper-fed flat die machines are operated by one man and an assistant. Fuller appreciation of the possibilities of the thread-rolling process has led to its use for rolling a variety of forms such as gear teeth, worms, splines, etc. Fig. 18 shows a selection of some precision rolled parts.

In addition to producing components to close dimensional tolerances, the work-hardened surface often eliminates the need for heat treatment operations and production times are usually a fraction of those required for machining. For example, by using a special purpose machine a $1\frac{3}{16}$ in. die shaft was spline rolled in four seconds instead of two minutes, which was required for hobbing. Significant economies can be effected in the production of gears by rolling, although in this instance several passes may be needed.

The last 10 years have seen continued development of work and die materials and also the introduction of more efficient thread rolling machines. For example, modern thread rolling machines (particularly those of the planetary type) can produce several hundred parts per minute. Thread rolling attachments and heads for centre lathes, capstans and automatic lathes (Fig. 19) are now proving very popular and whilst not usually as fast as special purpose rolling machines, are cheaper to buy and maintain. In the future we can expect this development to continue and also, possibly, the introduction of better die steels which will give better life, particularly with deep section rolling as in the case of gears and worms.

Precision rolling is, in fact, likely to replace more and more gear cutting operations and in some applications it is possible that rolling will be carried out on heated blanks.

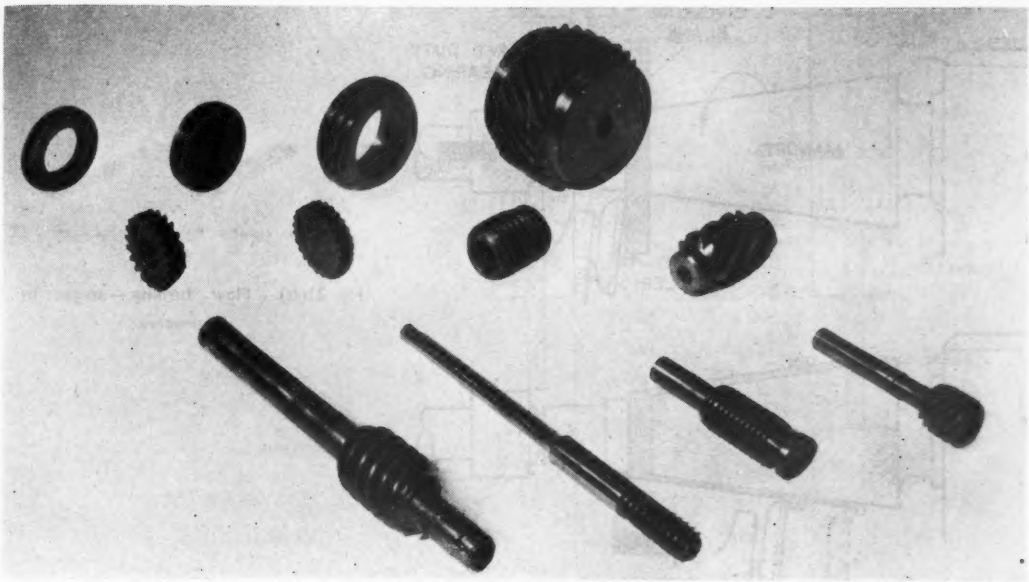


Fig. 18. Typical precision rolled components.

sheet forming

Sheet forming operations can be broadly divided into three groups, namely, punching and shearing; forming and bending; and deep drawing.

In the case of forming and bending operations, press and press brake forming is already well established. Rubber die forming is used on a limited scale particularly for soft materials and small quantities, and hydroforming (Fig. 20), in which the rubber diaphragm is backed by oil pressures, has potential applications far beyond those which have been reported to date; we can therefore look to further developments of this technique during the next

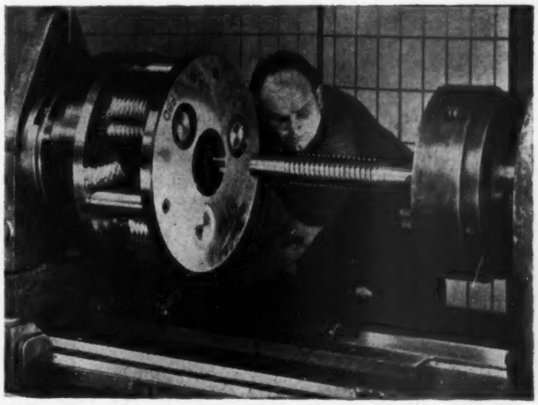


Fig. 19. Large thread rolling head in use on a lathe.

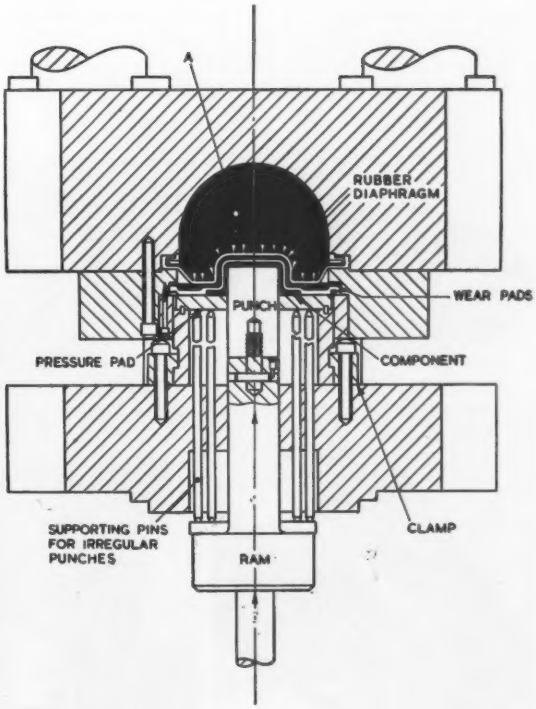


Fig. 20. Section of hydroforming tool.

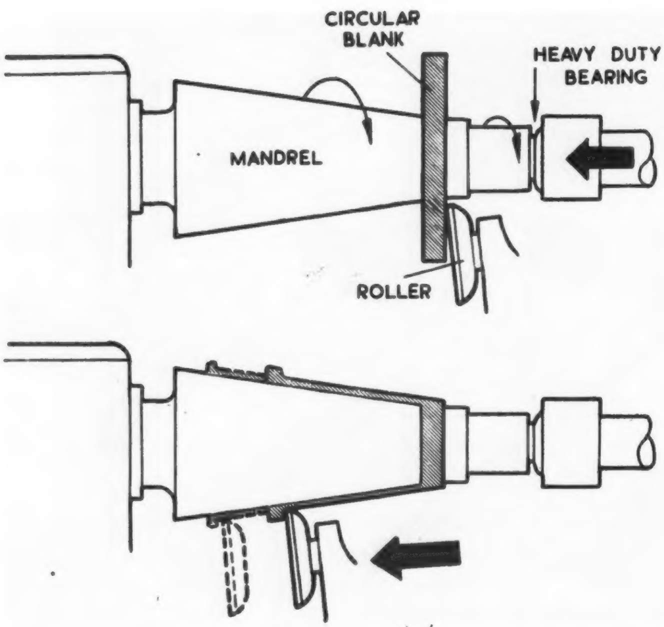


Fig. 21(b). Flow turning — stages in the process.

decade. Flow turning and shear spinning in which a metal blank is thinned and formed to shape over a mandrel (Fig. 21(a)) have been developed over the past 10 years, and various specially designed machines are now available for the purpose. This type of operation, particularly for the production of conical components, has already found a useful field of application in the aircraft industry and also to some extent in the production of domestic holloware (Fig. 21b), although it seems possible that the field for some of these applications in the future might well be taken over by explosive forming and high energy forming. Of the high energy forming methods already investigated, the compressed air type of machine (Fig. 22) and high voltage discharge forming appear to be particularly attractive and capable of being incorporated within a normal production line. Forming by liquid nitrogen has been reported by the U.S.S.R.

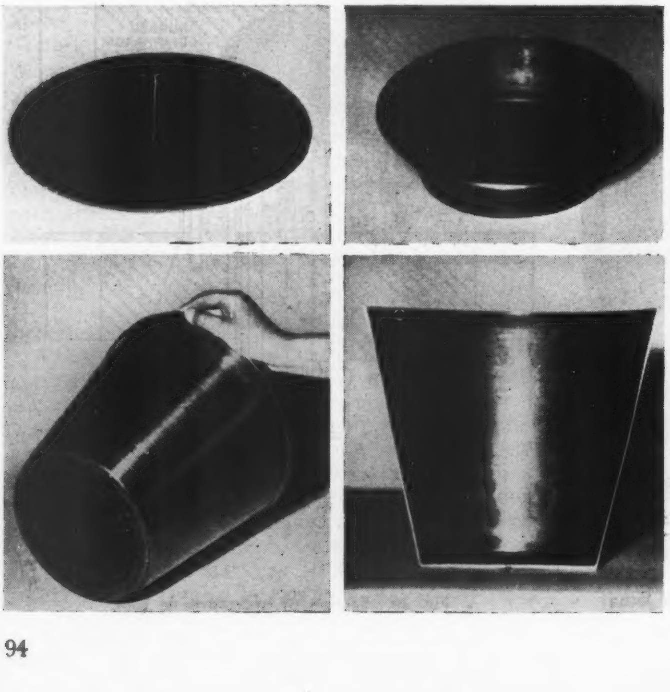


Fig. 21(b). Flow turning — stages in the production of a bucket.

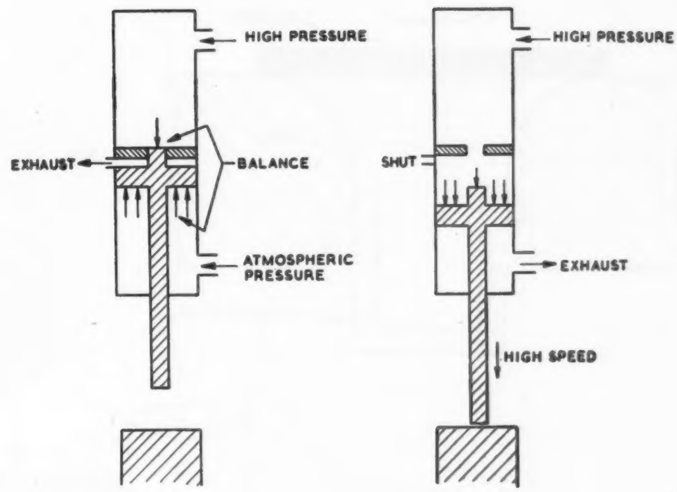


Fig. 22. Principle of high energy forming machine.

and the application of high hydrostatic pressure to improve the ductility of parts to be formed is likely to be further developed during the next few years.

The success of deep drawing is probably more dependent upon the quality of materials than any other sheet forming operation. For a great many years there has been no one accepted test that would differentiate between good and bad drawing properties but now, stemming from some of the pioneering work carried out by the late Professor Swift at Sheffield University, a cup drawing test that bears his name has been proposed and is being investigated by an International Committee. A view of the machine used for this test is shown in Fig. 23.

Another aspect of deep drawing that has been developed in recent years is the cupping of blanks without blankholder. A trumpet-shaped die is used (Fig. 24) and the technique is no longer solely applicable to very thick blanks.

Useful developments have also taken place in lubrication techniques. Highly reactive E.P. lubricants have been compounded and various surface treatments including zinc phosphate coating have been used with notable effect. Solid boundary lubricants such as graphite and molybdenum disulphide are now readily available and the extremely low friction substance known as P.T.F.E. may come into use for special applications and difficult draws in the future. Another interesting development that has arisen out of very recent work carried out at PERA, is the discovery that blank-holding loads considerably in excess of the loads required to suppress wrinkling can improve the state of lubrication existing between the tool and material interfaces and result in deeper draws from a lubricant of given viscosity. Fig. 25(a) shows the possible mechanism of lubrication during a deepdrawing operation when using high blankholder loads and the curves shown in Fig. 25(b) illustrate the effect of blankholder load on depth of draw when using mineral oils of varying viscosity.

A preliminary to almost all sheet and strip forming operations is the preparation of a blank, usually by blanking and piercing. The quality of blank required in terms of accuracy and finish depends partly on the quality required in the finished product and also, to

Fig. 23. Swift cupping press.

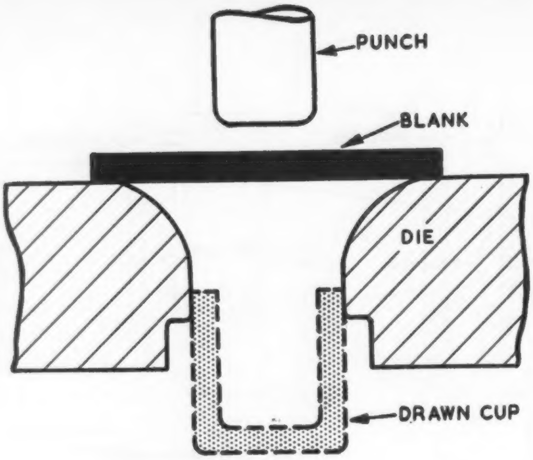


Fig. 24 (left). **Deep drawing without blankholder.**

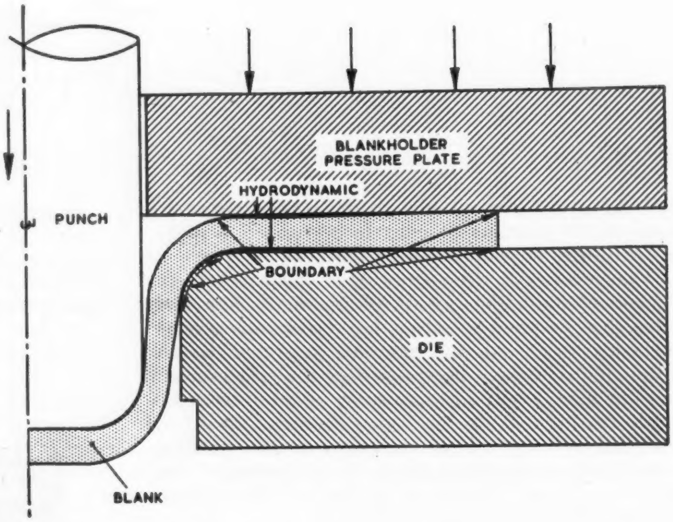


Fig. 25(a) (right). **Use of elevated blankholder loads in deep drawing — section of drawing tool showing probable conditions of lubrication.**

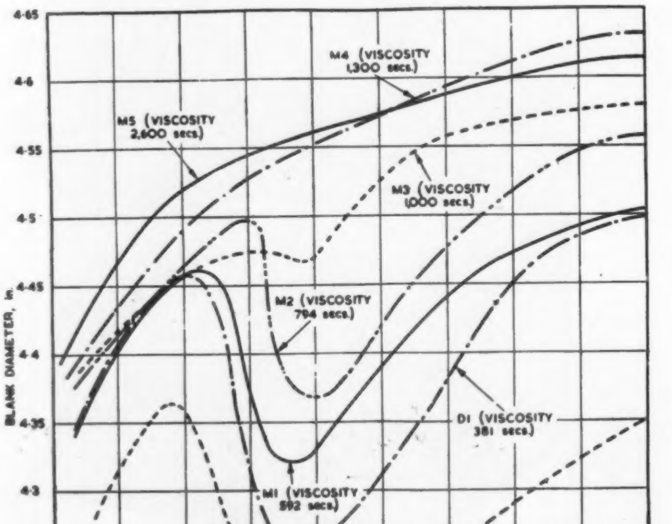


Fig. 25(b) (left). **Effect of blankholder load on depth of draw when using various lubricants.**

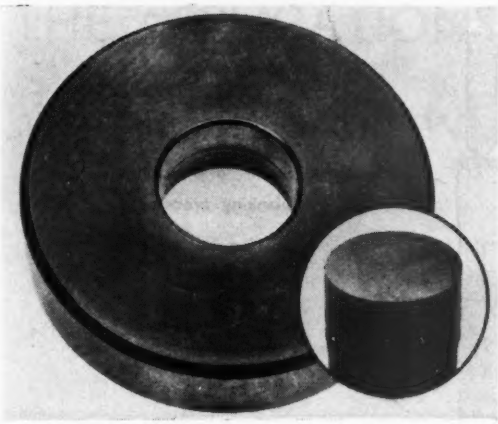


Fig. 27(a). Finish blanking technique developed at PERA. Radius edged finish blanking die with (inset) close fitting punch.

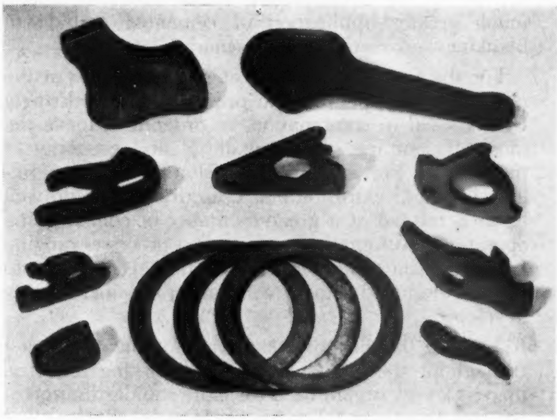


Fig. 27(b). Typical finish blanked components.

an increasing extent, on requirements imposed by the equipment and techniques used for subsequent forming operations.

During the last 10 years a great deal of practical research has been carried out in order to deduce optimum process variables and PERA, for example, have completed investigations into punch/die clearance and finish blanking. Fig. 26 shows the effect of punch/die clearances on punch load and stripping force for four different materials. Industrial applications of finish blanking using a suitably radiused die and small punch/die clearance are increasing rapidly (Fig. 27) and valuable savings have already been reported as a result of the improvement in sheared surface condition made possible by this technique. A good example of this is the copper contact component shown in Fig. 28. Probably one of the reasons why this technique is so popular is that it can be used on standard presses.

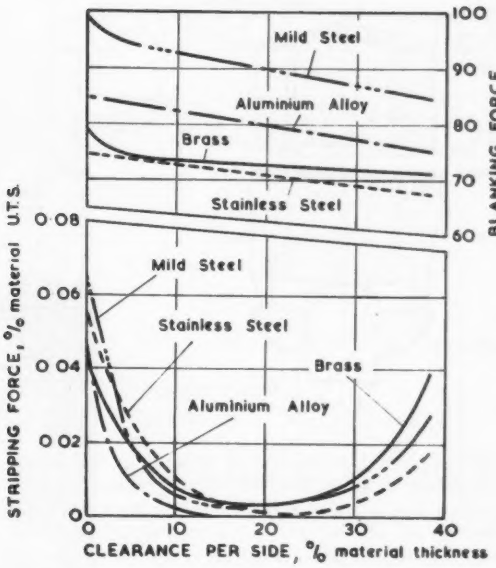
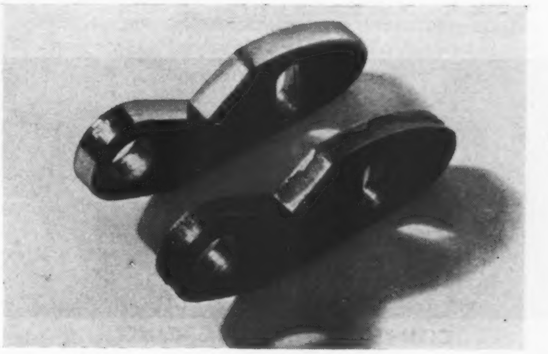


Fig. 26. Effect of clearance between punch and die on blanking force and stripping force.



FINISH BLANKING

OLD METHOD	NEW METHOD BASED ON PERA RECOMMENDATIONS
1. BLANK 2. FLATTEN 3. MILL EDGE 4. HAND FILE EDGE	1. FINISH BLANK
COST PER 50,000 COMPONENTS £2,200	COST PER 50,000 COMPONENTS £900
TOTAL SAVING = £1,300	

Fig. 28. Finish blanking of a copper component.

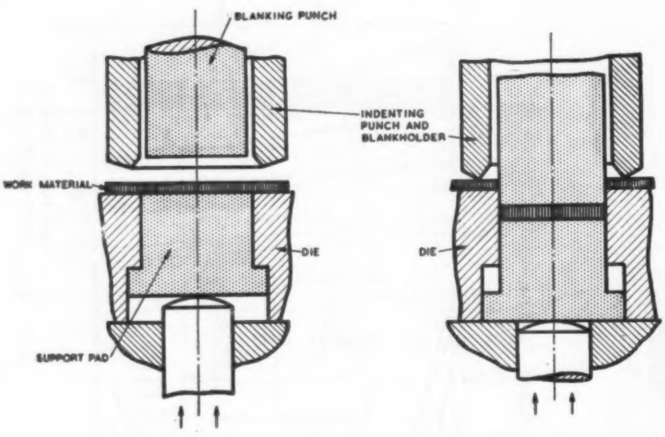


Fig. 29. Principle of double-action fine blanking process.

Another recently introduced technique for precision blanking which originated in Switzerland employs a blankholder to control and hold the work material in the region of the die. This technique, which is shown schematically in Fig. 29, requires a special press and would appear to be mainly applicable to thin components.

One of the most recent developments which has been patented by PERA is a technique of finish piercing by which holes can be produced largely without distortion and with equivalent accuracy and finish to drilled holes. A comparison of the hole surface condition obtainable with conventional and finish piercing is given in Fig. 30. This technique is already being applied in industry and use of it is likely to extend considerably in the next few years. Within the next decade it is likely also that there will be further developments in die materials, and a much greater application of cemented carbide to blanking and piercing tools generally.

For the future, it seems probable that more of the metal forming operations at present being used singly will be used in combination, in order to achieve the most efficient use of raw material and economy of production. For example, precision hot forging followed by cold extrusion and deep drawing could well be used instead of a greater number of cold forming operations. Automatically controlled processes ranging from the single numerically controlled machine to fully automated lines will also be increasingly developed.

Turning finally to a matter of general interest throughout the whole of the pressworking industry, there is a very urgent need for more standardisation of press and press tool dimensions. It seems illogical that most press tools have at the moment to be used always on the same or identical press for which they were originally designed!

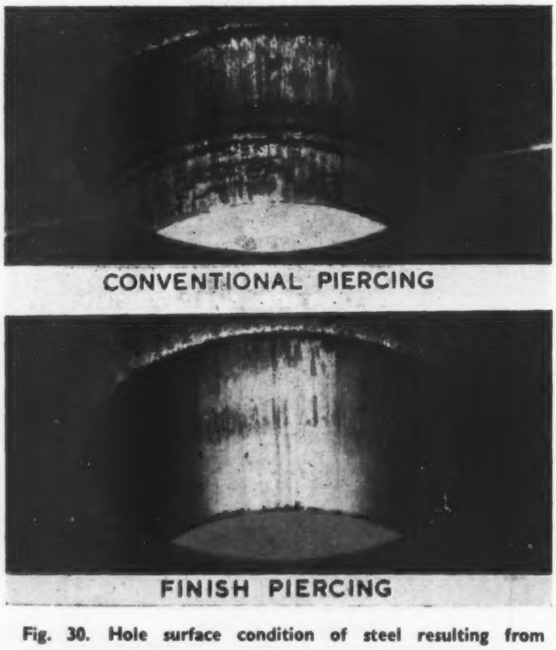


Fig. 30. Hole surface condition of steel resulting from conventional piercing and PERA finish piercing technique.

acknowledgments

The author wishes to thank the Production Engineering Research Association for permission to use certain of the Association's research results, and the Atomic Energy Research Establishment, Harwell, for permission to use examples from work carried out for that Establishment. Acknowledgments are also due to various firms who supplied information, and to the following for the supply of photographs:

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THE APPLICATIONS OF CONTROL SYSTEMS TO JOBBING AND BATCH PRODUCTION

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The proceedings of Sessions II and III of the Symposium on " Machine Tool Control Systems", organised by The Institution of Production Engineers at The College of Aeronautics, Cranfield, in August, 1960, are reported on pages 99 - 138.

The proceedings of the fourth and final Session will appear next month.

EVERY day the production engineer's problems become more complex and production management finds increasingly difficult the efficient integration of its varied activities. To assist in these fields more and more electronic equipment is being devised and applied. For example, the monitoring of continuous flow process work can be achieved with relative simplicity and the expediting of production control documentation by digital electronic equipment is now beginning to be introduced. In the actual manufacture of engineering components, a modern approach is available in the computer-controlled machine tool, which can produce the geometric profile required by the designer by controlling the machine tool with a tape bearing encoded data calculated directly from the designer's functional dimensions. This Paper records the experience of the Royal Ordnance Factories in introducing and using this type of equipment.

the Royal Ordnance Factories

The Royal Ordnance Factories produce a wide range of armaments and associated equipment for the fighting services. In the engineering field their products range from instruments and electronics to heavy guns and armoured fighting vehicles. Little of this work is required, in normal times, in what could be considered commercially as production quantities. Changes in design often occur during actual production and, in addition, there is always a high proportion of experimental and development work.

It is the policy of the Controllerate of the Royal Ordnance Factories to keep well to the forefront of modern practice by installing new machines and introducing new processes and techniques, to improve or to expedite production, to meet more exacting service requirements, or to reduce production costs.

Early in 1956 the Royal Ordnance Factories became interested in the new electronic control equipments being introduced by both E.M.I. Ltd. and Ferranti and their application to the control of the movements of machine tool elements to close tolerances. Following investigation, it was decided to introduce into the Royal Ordnance Factory, Nottingham, machine tools of normal character fitted with the two different methods of control.

Cincinnati No. 3 Vertical Milling Machines were supplied to both companies for adaptation and the addition of the control gear, and were received back into Royal Ordnance Factory, Nottingham in the early months of 1958. One machine was equipped with Ferranti magnetic tape control in three dimensions whilst two machines were equipped with the E.M.I. paper tape control in two dimensions only. Later a third machine was completed by E.M.I. Ltd., this again having the control operating on the two horizontal motions.

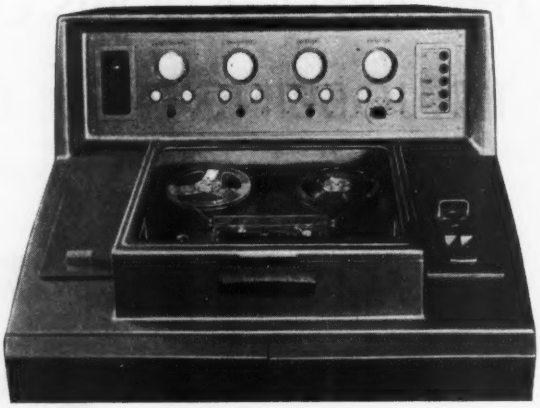


Fig. 2. Reader unit.

the Ferranti control system

Fig. 1 shows a general view of the Ferranti-Cincinnati machine. This system of automatic control uses a magnetic tape which when "played" causes the machine table and head to move in accordance with a planned programme. This programme is determined from data from the component drawing and the related cutting requirements, and is first punched in codified form into a punched tape. This is fed into a digital electronic computer which processes the information and records the resulting control signals on the magnetic tape in form of trains of pulses, which are deciphered by the "reader" unit of the machine when the tape (Fig. 2) is "played".

An electro-optical system is used to monitor each movement of the slides. Linear measurement is achieved by fitting to each axis a photo-electric equipment to read the movement of a short length of diffraction grating past a fixed length attached to the non-moving member. These readings also are in the form of pulses and null the servo system for any particular traverse when the table movement corresponds to that required by the input of pulses from the magnetic tape. Continued motion is a steady stream of pulses and the rate at which they are read in decides the speed of movement, and the total number of pulses represents the displacement from a datum point. Profiles are obtained by a combination of two or three movements in continuous relativity to the datum, which is a pin to which the cutter is set by hand before commencing profiling. Figs. 3 and 4 show a diffraction grating and the basis of its operation.

The control system is fitted to a standard Cincinnati No. 3V Vertical Milling Machine on which hand controls and feed gearing were removed from the longitudinal and transverse table movements, and from

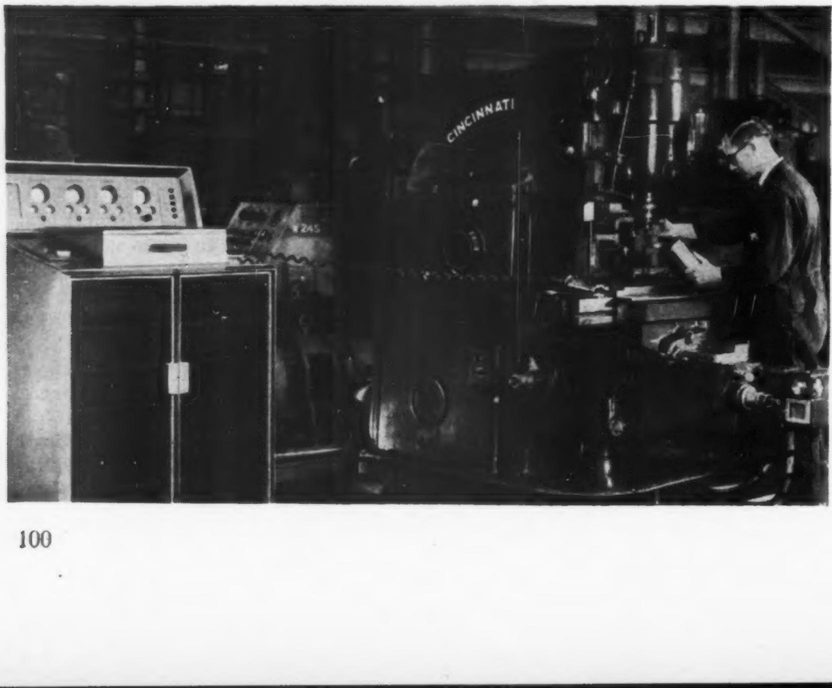


Fig. 1. General view, Ferranti - Cincinnati machine.

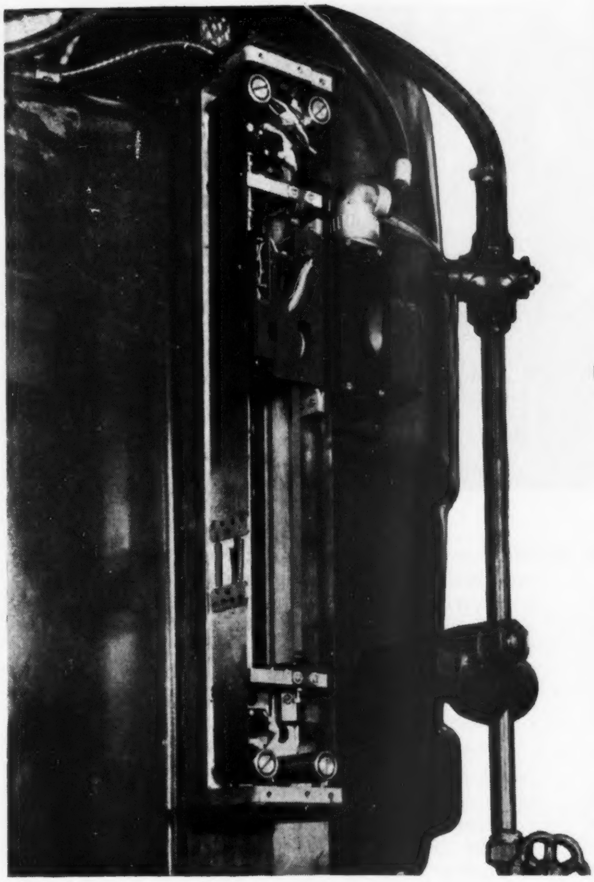
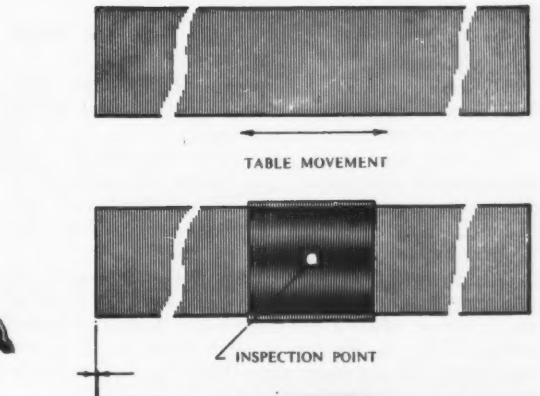


Fig. 3 (left). Diffraction grating (in vertical axis).

Fig. 4 (below). Showing operation of diffraction grating.



the vertical movement of the cutter head, before fitting electro servo motor units. The servo motor, tachogenerator, and gearbox for each axis is contained in a housing fitted on the extremities of the machine slides. The units are identical but the method of transmitting their motion to the table differs from the transmission to the quill head. Here a second gearbox is introduced between the head and its servo motor to connect with the rack and pinion drive to the quill head. The output of the gearboxes to the horizontal motions of the machine table is through recirculating ball nut and lead screw systems.

The longitudinal travel of the table is 34½ in., transverse movement 16¼ in. and the quill head will move 6¼ in. vertically. The maximum feed rate is limited by the machine and computer output to 15 in. per minute.

An emergency stop button is provided on the machine head.

The high cycle power supplies (a) and (b) required for the control equipment, are supplied from a motor alternator set sited at the rear of the equipment:

(a) 115 Volt 400 cycles three phase 1.5 KVA Smooth.

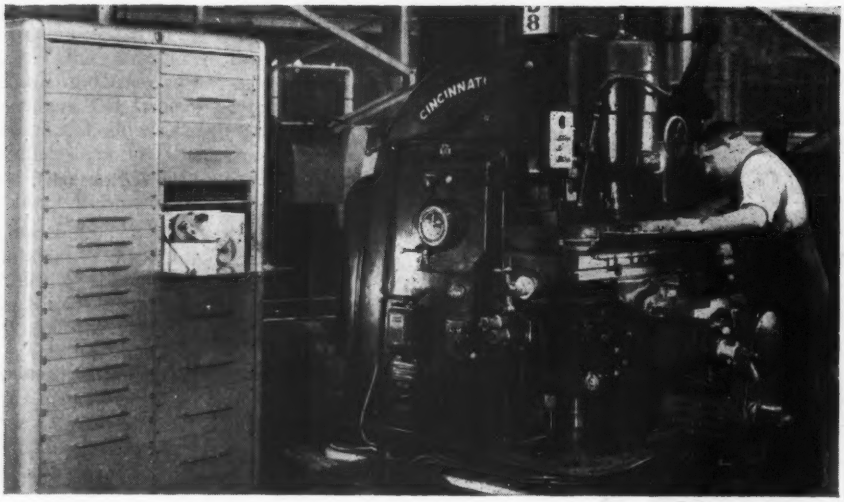


Fig. 5. General view, E.M.I.-Cincinnati machine.

(b) 115 Volt 400 cycles three phase 10 KVA Coarse.

The 230 Volt 50 cycle single phase supply and 400 Volt 50 cycle supply for the basic motor drives are provided from the factory mains.

The total floor space occupied by the machine and its associated equipment is just under 250 square feet. The teletypewriter and paper tape reading units are installed in a programming office apart from the production floor.

A system of checking the input which governs movement is incorporated, which automatically stops the machine when a pre-determined tolerance is exceeded. This is set for a total error in all three movements of not more than 0.0032 in. in 2 seconds or 0.012 in. instantaneously.

The tape can be rewound on the machine before being removed for storage until it is needed again. When profiling, if the tape is stopped other than at a programmed point, synchronisation of the table with the tape is lost and the cutter must be reset to the datum point and the cut started again.

the E.M.I. control system

Fig. 5 shows a general view of the E.M.I.-Cincinnati machine. This system of automatic control generates two dimensional contours which are defined by a series of cartesian co-ordinates. These co-ordinates are calculated from the component drawing and punched into the paper tape. When this is fed into the machine control, further calculation is done electronically to obtain a large number of intermediate points and to transmit this control data to the machine slides. In this manner smooth curves are obtained between the basic points. These interpolated positions calculated within the control system are transduced as analogue voltages, and as such can be compared with the analogue voltage representing the angular displacement (from its datum position) of the lead screw operating the slide. Where this comparison shows a difference this is amplified and used to initiate the operation of the servo motors which move the slide to the correct position, the servo action ceasing when the two analogue signals are identical. Thus the position of a cutter relative to the work table is uniquely defined by two such sets of control applied to the longitudinal and transverse motions of the machine table.

A standard Cincinnati No. 3V Vertical Milling Machine was modified by the removal of the hand controls and feed gearing from the longitudinal and transverse movements of the table, and by substituting the electric servo motor assemblies to operate the respective table movements. These assemblies (Fig. 6) contain position identifying units, servo motors and tachogenerators.

Originally work hardened lead screws with recirculating ball nuts were fitted to operate the slides,

Fig. 6. Table end units (E.M.I.).

FRONT SIDE

Drawing Office Please Supply Control Tape for EMI/Ferranti 3V Cincinnati Miller to the following instructions

Drwg. No.................................
Op. No.....................................

		E.M.I.	Ferranti	
CUTTER DIA.	Roughing			
	Finishing			
Is Cutter Compensation to be Programmed ?				
Are Two or more tapes to be produced ?				
Amount to be Left Oversize per surface For :-	1st Roughing			
	2nd Roughing			
	Finishing			
MAX Feed Rate (INS/MIN)			Roughing	
			Finishing	

Remarks :—

Date :—

Signature...................................**Planning Office**

REVERSE SIDE

Planning Office Detailed below is information necessary for Compilation of Master Operation sheet.

Drwg. No.................................
Op. No.....................................

	E.M.I.	Ferranti
Maximum Distance Between Spans		
Total No. of Spans in Cycle		
Distance Travelled (Run in and out)		
Distance Round Path of Centre of Cutter		
Position of Component Fixture on Base Plate		

Remarks :—

Date :—

Signature...................................Drawing Office

Fig. 7. Inter-departmental information card.

but later these were replaced by hardened and ground lead screws also having recirculating ball nuts. The full longitudinal travel of the table is limited to 29.999 in. and it has 14 in. of traverse. Height setting is achieved by hand or power operation on the machine head. The feed of the workpiece past the cutter was recommended not to exceed 10 in. per minute. This is more than adequate for the normal product and smaller feeds are more usual to maintain accuracy and surface finish.

The machine tool and control cabinet occupy some 230 square feet of floor area, the machine operating from the normal factory power supplies of 400V. 50 cycles per second 3 phase and 230V 50 cycles per second single phase. A relay has been arranged to stop the tape which operates on a single phase supply if the cutter stops due to failure of the main power supply.

Cutter compensation can be made in steps of 0.0001 in. up to 0.3 in. on diameter and can be brought in or out by the operator or by the tape control programme. The unit can be seen opened on the control cabinet, Fig. 5.

As the position in this system is defined uniquely it is unnecessary to return to the starting datum point following a stop.

pre-production procedure

The Planning Department of the factory prepares from the drawing a schedule of operations and the raw material requirement for a component. When it is intended to produce a contour on an electronic profiling machine, this will be stated on the operation schedule which is sent to the Drawing Office for the subsequent calculation and tape preparation. These calculations are made in conjunction with the practical machining data recorded on a card (Fig. 7) which gives details of cutter diameter, cutting speed, feed rate, number of cuts, and further information relating to the method of carrying out the work. Which control system is to be employed is decided by the

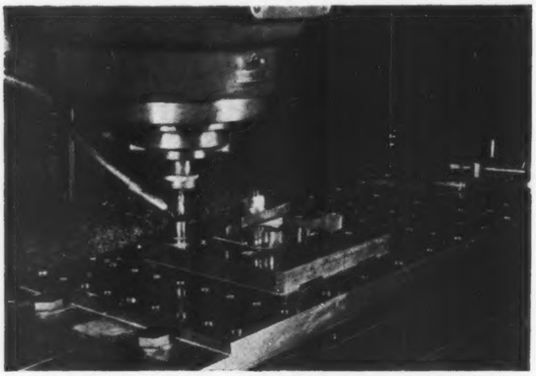


Fig. 8. Base plate.

accuracy and the finish required and, of course, by the work load on the machine.

The Drawing Office carries out the mathematical calculation work, prepares the punched tape and designs any necessary fixtures. These fixtures establish a relationship between the machine absolute datum (zero lead screw displacement readings in the E.M.I. system) and the positioning of the component, and they are of simple construction. Two pins in the base of the fixture are provided to locate in two of the reamed holes in the base plate, the upper face of the fixture carrying the workpiece and any clamping attachments that are necessary. A base plate was manufactured for each machine containing a large number of jig bored dowel holes and ½ in. B.S.F. tapped holes : these plates position fixtures accurately relatively to the datum and in alignment with the machine slides (Fig. 8). The reamed holes which act as location points for the fixtures are stamped in both axes from datum — A1, etc., and each small fixture when made has its locating dowels stamped to correspond with the holes into which it must be fitted.

The use of this master base plate enables interchange between any of the machines and ensures, in the case of the E.M.I. machines, correct positioning in relation to the absolute datum.

The proving of the paper tapes in the E.M.I. controlled machines is carried out by tracing the profile, with a pencil held in the cutter collet, on a sheet of paper laid on the machine table.

This checking procedure is not done with the Ferranti machine as a line drawing is supplied with the magnetic tape from the computer centre.

All paper tapes carry the drawing number of the component, the fixture drawing number, and the diameter of the cutter used, but each tape is also identified uniquely to avoid error as two tapes may be produced for one component either to cut by two methods or to produce by two separate cuts.

programming

The use of automatically-controlled machine tools demands that much more detailed planning is carried out initially than is common in most jobbing or batch production shops. The programmer, in addition to understanding the capabilities and limitations of the control system, must be thoroughly conversant with machining techniques and will, in preparing his programme, specify the size of cutter, direction of cutting, run-out points, and the rate of feed. This information, together with the geometric data calculated from the drawing, is encoded into a form suitable for the machine it is intended to use.

Ferranti system

There are four stages needed to produce a component :-

1. the programme is produced from the drawing and the ancillary information of cutter size, datum point, etc.;
2. this is then encoded into a punched paper tape;
3. a digital electronic computer using the punched paper tape as input carries out a programmed calculation to determine a series of co-ordinates completely defining the cutter path, and records the necessary command pulses on a magnetic tape;
4. the machine tool control console is operated automatically by the magnetic tape to carry out the cutting operation.

With this system only the co-ordinates of the change points in the geometry of the component and of the centres of arcs of circles are needed, and these are specified in relation to a datum point to an accuracy equal to a single pulse of the machine system, i.e., 0.0002 in. Code instructions indicate types of profile, operating signals, and the geometric data, and are so encoded as to operate an inbuilt checking system in the control.

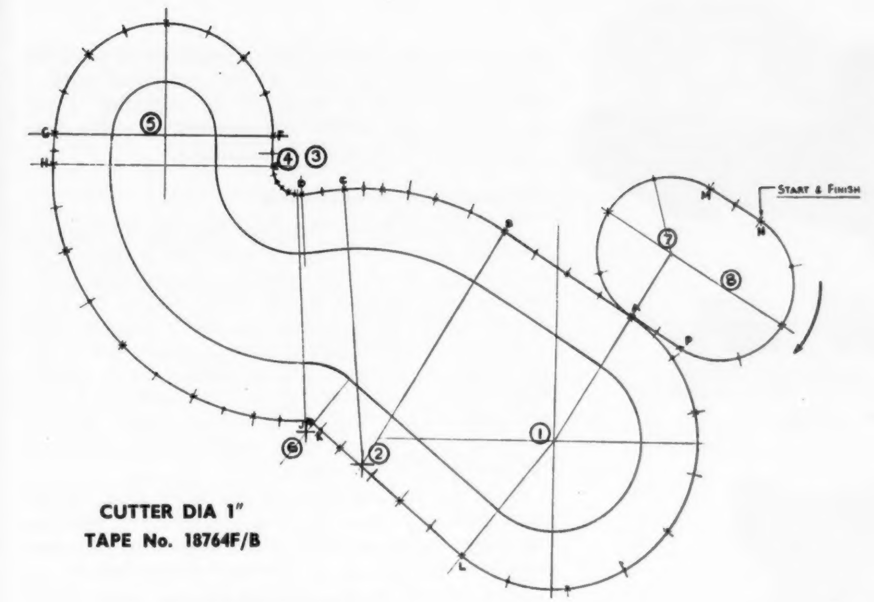
If more than one magnetic tape is required to complete a component, a second tape can be used starting from the same datum point as the first or from a programmed stop point in the first tape. Two cuts can be taken either by using a roughing cutter smaller in diameter than the size of the programmed finishing cutter or, alternatively, using only one cutter but two magnetic tapes, the tape for the roughing cut being programmed for a larger cutter than that actually used.

After the programme has been punched and corrected, a typewritten print-out is produced from the tape reader which is sent with the paper tape to the computing centre.

E.M.I. system

The contour to be profiled is notionally divided on the drawing into its constituent geometric sections and co-ordinates calculated for each change point.

One of these data points will be the last defined point of one continuous piece of contour and the first point of the next. Intermediate data points are computed, their spacing governing the accuracy of profiling and the feed rate. The closer the data points the more accurate the profile but the slower the rate of feed. Additional points may have to be



CO-ORDINATES

Section	Minor X	Minor Y	Major X	Major Y
N			11·408	4·335
N	11·152	4·636	11·239	5·022
P	11·540	5·278	11·926	5·191
A	12·140	5·062	12·354	4·932
A	12·635	4·762	12·916	4·593
B	13·197	4·423	13·478	4·253
B	13·765	4·106	14·065	4·002
B	14·298	3·953	14·534	3·928
C	14·693	3·925	14·854	3·934
D	15·040	3·951	15·226	3·967
D	15·282	3·964	15·336	3·948
D	15·384	3·914	15·421	3·870
E	15·445	3·817	15·453	3·759
F	15·453	3·640	15·453	3·520
F	15·522	3·163	15·720	2·858
F	16·034	2·643	16·406	2·567
F	16·778	2·643	17·092	2·858
G	17·290	3·163	17·359	3·520
H	17·359	3·640	17·359	3·759
H	17·327	4·119	17·234	4·469
H	17·024	4·889	16·725	5·252
H	16·444	5·479	16·128	5·655
H	15·873	5·749	15·609	5·808
J	15·388	5·831	15·170	5·830
J	15·153	5·831	15·136	5·835
K	15·120	5·842	15·106	5·852
K	15·028	5·918	14·846	6·072
K	14·586	6·292	14·326	6·512
L	14·066	6·732	13·806	6·953
L	13·386	7·187	12·870	7·241
L	12·376	7·081	11·990	6·734
L	11·779	6·259	11·779	5·741
A	11·990	5·266	12·354	4·932
A	12·610	4·631	12·523	4·245
M	12·222	3·989	11·836	4·076
N	11·622	4·206	11·408	4·335

Change Point	Centre Point	Co-ords. of Centre X	Co-ords. of Centre Y	Angle	Radius
A	1	13·000	6·000	+58°51′	1·248
B	2	14·653	6·197	+58°51′	2·272
C	2	14·653	6·197	+84°56′	2·272
D	3	15·244	3·759	+84°56′	0·209
E	3	15·244	3·759	+ 0°	0·209
F	5	16·406	3·520	+ 0°	0·953
G	5	16·406	3·520	+ 0°	0·953
H	4	15·284	3·759	+ 0°	2·075
J	4	15·284	3·759	+86°52′	2·075
J	6	15·165	5·921	+86°52′	0·091
K	6	15·165	5·921	+49°47′	0·091
L	1	13·000	6·000	+49°47′	1·248
M	7	12·095	4·504	+58°51′	0·500
N	8	11·667	4·763	+58°51′	0·500
P	8	11·667	4·763	+58°51′	0·500

Fig. 9. Component and Co-ordinates of Cutting Path for E.M.I. Machine

inserted, even if the contour is a straight line, to ensure the span between any two points does not exceed 2 in., as this is a limitation of the interpolater in the control. The series of co-ordinates calculated represent the path of the centre of a cutter of a selected diameter and not the profile of the component. These are arranged to refer to a local datum determined by the positioning of the component in relation to the master base plate on the machine, and before the actual tape can be punched each pair of co-ordinates must be increased by the displacement ordinates of the local datum from the absolute datum of the machine. Fig. 9 shows a component dimensioned and the co-ordinates of the cutter

Fig. 10. E.N.30.

Fig. 11. E.N.5.

Fig. 12. 5/8 in. aluminium.

Fig. 13. 1 1/16 in. mild steel.

path tabulated. Whilst this information is punched into the paper tape in binary coded decimal form, a teletype print-out is produced for checking. Tapes can be corrected simply and speedily or a new tape produced at short notice, if required.

the machines in operation

The Shop at Royal Ordnance Factory, Nottingham in which these machines are employed is engaged in the production of high precision mechanism parts, mainly from medium tensile steels. This is the type of component the machines are set to produce and is either a standard service part in day-to-day batch production by orthodox milling methods or an experimental detail demanded in small quantities, that is, the components worked upon are normal factory products and not examples devised to demonstrate the machines' performances.

From its introduction records were kept of the work done on each equipment, of setting and machining times, of fixture costs, of the amount of maintenance and the time of, and reasons for, stoppages.

Figs. 10 - 16 show examples of the work which has been carried out on these machines. The graphs (Figs. 17 - 20) show unit cost and delivery period plotted against quantity on demand for examples 10, 11, 12 and 14. None of these components has actually been produced by all the methods quoted nor, of course, has a batch of every size considered been manufactured. Some components have been produced previously by standard equipment; in these cases actual comparison is possible. In other cases the cost of production can be determined as adequate basic data for orthodox methods exist. It is thus possible to compare the cost of manufacture of these components by four or five methods in varying batch sizes. Estimates have been made for delivery time based on the normal factory characteristics; these, of course, are peculiar to the unit under consideration and within that unit could vary due to internal causes. Therefore, whilst the figures should not be regarded as absolute, they can be accepted as expressing accurately a relativity.

The higher capital cost of the adapted machine tool fitted with the electronic equipment results in a measurable increase in the hourly machine rate. In comparisons with the normal type of machine, this will be of the order of 35% for the magnetic tape controlled machine and around 20% for the machine controlled by punched paper tape. In assessing the hourly rates, no element was included for the programming time needed for the tape controlled machines, as this was deemed to be offset by a reduction in Drawing Office time spent on fixture design. (Generally the fixtures for the electronic machines prove to be less expensive than those for the corresponding standard machine tool.) Other than in this respect the hourly rate used was a comprehensive value incorporating machine tool amortisation, apportionment of general overhead costs and labour but excluding material cost.

It early became evident that the greater proportion of the profiling work required was of only two-

dimensional nature: components with bosses or faces at more than one level can be machined by appropriate adjustment of the quill head; this still applies when two separate programmes are needed to produce two overlapping profiles in plan. For this reason, the machine hour rate used in costing the production of the examples by the magnetic tape machine has been assessed on what the cost of the machine would have been with two dimensional control only.

The first point that emerges from a study of the graphs is that when profiling contours (by vertical cutter methods) the normal milling machine is at a distinct disadvantage, and that some form of specialised approach, either by copying attachment or electronic profile control, will have considerable economic advantage. Between normal copying machines and electronic plant, it is clear that small quantities are almost always cheaper when produced by the latter. The size of batch at which the break-even point in cost will occur will vary between different components from a few to several hundreds and is dependent on the complexity of contour, depth of cut, amount of stock to be removed and the required accuracy and finish. This change-point will also be affected by some secondary factors which are of a domestic nature, e.g., differing labour rates between machines, setters relative rates if employed, and the actual computed machine hour rates.

Both initial production and the completion of the batch are achieved sooner when using the tape-controlled machines within the range of quantities considered in the graphs, although with some components it has been found that the three-spindled copying machine can build up to a greater hourly output than either tape-controlled machine. In some instances, the necessary time wait between order and commencement of production has been reduced by 80% and in nearly every case a considerable reduction can be made. One main reason for this is that workpiece locating fixtures, together with a profile template or hardened copy plate, are necessary to tool up a conventional machine. With tape-controlled machines neither copy nor template is needed and if a fixture is required at all, it is of very simple construction saving considerable Tool Room time, and proving much less expensive. The provision of the master plates mentioned earlier has also contributed to this fixture simplification and although the initial cost of these was appreciable, they will function throughout the lifetime of the machine and in consequence, have little effect on the cost of any one component.

Fig. 14. E.N.24.

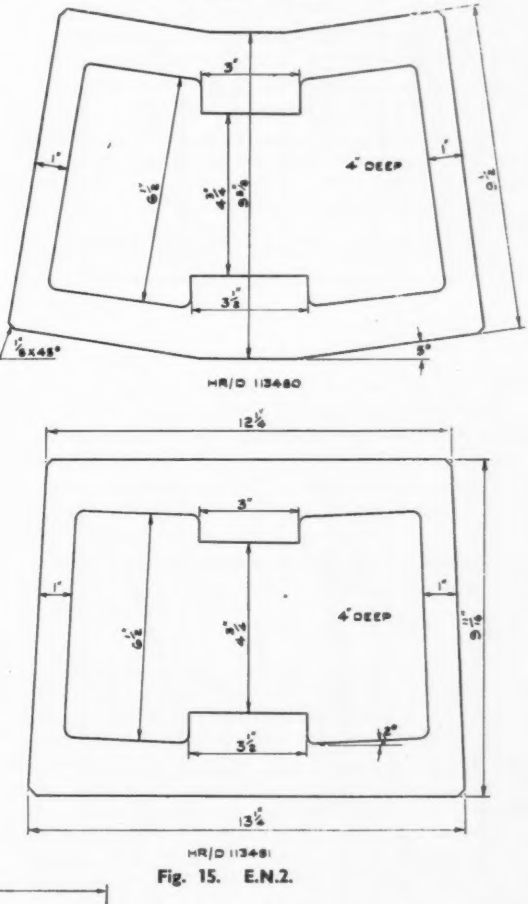


Fig. 15. E.N.2.

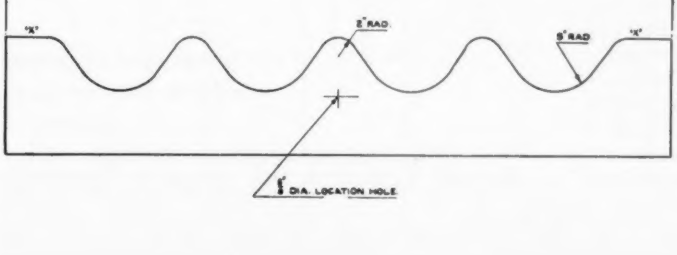


Fig. 16 (left). ½ in. aluminium.

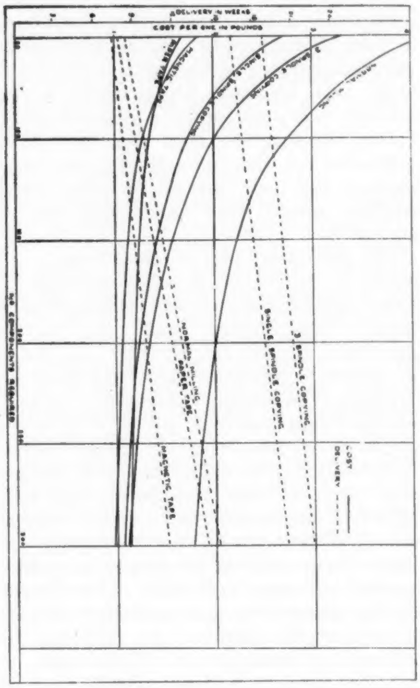


Fig. 17.

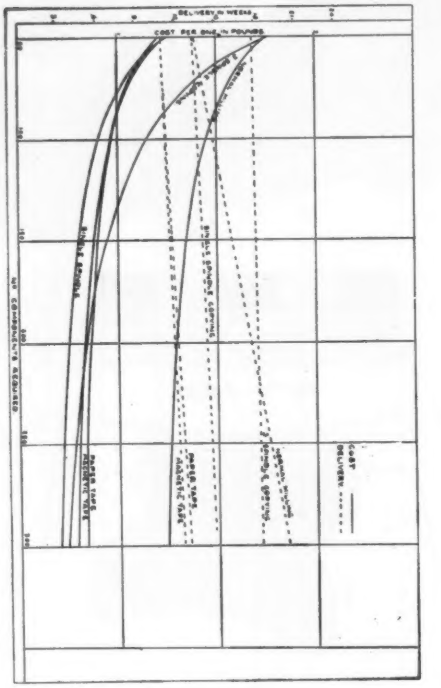


Fig. 18.

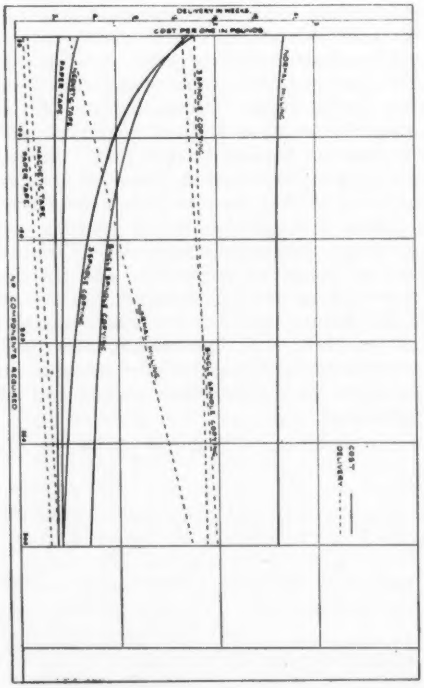


Fig. 19.

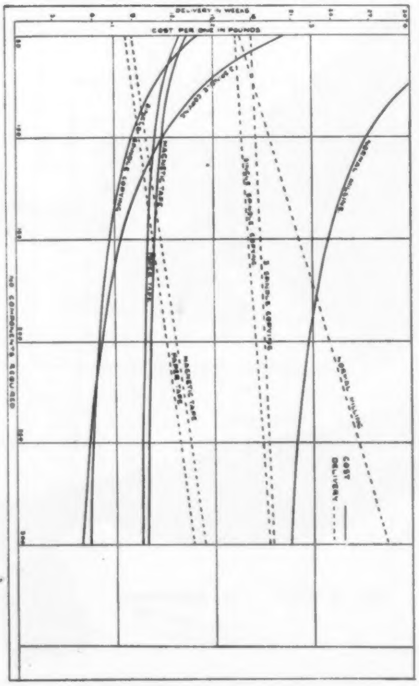


Fig. 20.

	Magnetic Tape	*Paper Tape*	*Normal Milling*	*Single Spindle Copies*	*Keller 3-Spindle Copying Machine*
Example 1	50 incl. tape	32 incl. tape	140	98	130
Example 2	53 incl. tape	44 incl. tape	60	60	120
Example 5	40 incl. tape	24 incl. tape	105	65	120

Fig. 21. Comparative cost in £'s.

Fig. 21 shows the comparative costs in £'s of fixtures for different methods for Examples 1, 2 and 5, shown in Figs. 17, 18 and 20.

The time taken for the paper or magnetic tape to be produced from the completion of the Drawing Office calculation work is small, and when urgency exists could be concurrent with the fixture manufacture. The Drawing Office calculation work mentioned is not peculiar to the tape controlled machines; identical or very similar work is necessary in the design of fixtures and copies or templates for normal machines.

Fig. 13 shows a soft template in $\frac{1}{16}$ in. thick M.S. plate required to be within a tolerance of ± 0.001 in. This was produced on the magnetic tape machine within these limits; production by any other method would have involved hand fitting after machining. Although only one was required, the cost including tape was slightly less than by normal production method and had a dozen been required, the cost would then have been about one-third of that by the normal method. A number of templates (one off) for production use have been produced in this manner.

Fig. 15 shows two similar components which were urgently needed. As the tolerances were sufficient to allow of their production by the paper tape controlled machines without subsequent fitting, the requirement of two off each were so produced, the cost being around 60% of the estimated cost for normal milling.

The example in Fig. 16 required a longitudinal traverse of 63 in. It was profiled in two settings on the magnetic tape machine. (Three settings would have been needed on the paper tape machine.) Both programmes were carried on the one magnetic tape and the work produced within ± 0.003 in. in the two settings. The material was $\frac{1}{4}$ in. thick aluminium. The cost by electronic machine was greater than if made by horizontal boring and milling independent of the quantity demanded. This is largely due to processing ten at one setting as against four on the electronic equipment.

operating experience

magnetic tape machine

advantages

The measuring system is free from friction and wear and is located in close proximity to the workpiece whilst remaining independent of the table operating drive.

Only changepoints in the geometry of the component need to be provided for by the programmer, the necessary series of intermediate steps required in practice being calculated by the electronic computer.

Accurate cycle times and machine loading can be assessed as the cutting speed is fixed by the programme.

A safety device is incorporated which will stop the machine and apply brakes to the servomechanisms in the event of a power supply failure, an incorrect reading, a failure in the electronic circuits, or a deviation of measurement between the tape record and the measuring system in excess of a set tolerance.

disadvantages

The magnetic tape has to be produced outwith the factory and returned if alteration is needed.

No compensation exists for variation in cutter diameter.

Once programmed the feed rate cannot be altered to allow for variations in size or machinability of a component.

Once a non-programmed stop has been made the cutter must be returned to the setting datum and the profile retraced.

comments

To date (June, 1960) the machine has run some 3,800 hours. It has maintained accuracy and surface finish of a high standard and repeatability to an accuracy of $\pm$ .0015 in. Most dimensional variations have been due to cutter wear. Heavy cutting worsens the surface finish but generally does not seriously affect accuracy of dimension, although very heavy cutting in hard material can do so, particularly if the tooth loading is high. These factors have to be appreciated in relation to the finish and accuracy required when the initial programming action is being undertaken.

Cutter setting to the datum pin can be done with a slip bush but greater accuracy is achieved using a dial gauge reading to 0.0001 in. in the collet.

Rapid reversal of a traverse must be avoided, as the reversal pulses will cancel out the existing forward pulses instead of this being done by the negative

feed-back from the diffraction grating readings. At any one time these errors are small but they can accumulate to commensurable size in a large and complex contour. They can be avoided by programming a smaller feed rate to operate when approaching a point where reversal takes place.

Tape life has been found to be of the order of 450 playings over a period of approximately 18 months, after which the signals in the checking register approach the maximum allowable error of the control system.

Many minor difficulties have been overcome in the programming stage by alterations in technique and in application. This has contributed to the steady increase of machine availability from the time of installation to date which is now the order of 93% compared with 77% a year ago.

paper tape machines

advantages

The necessary computation for the production of the control tape is carried out and the tape punched up on site, eliminating transport and any external service.

The paper tape has proved reasonably robust and not easily damaged in the machine shop. Modifications can be carried out quickly and simply or a new tape reproduced within the factory.

The cutter compensation unit allows roughing and finishing cuts from one tape, adjustment for variation of cutter diameter due to regrinding, and compensation for inaccuracies arising from the machine spindle.

The system of unique positional definition allows a cut to be stopped and restarted at any point, no return to datum being required.

The variable feed rate enables adjustment to be made to the programmed speed when machining components which are dimensionally or materially inconsistent.

disadvantages

The position identifying system measures the angular rotation of the lead screw and sizeable discrepancies between the actual and " read " positions often exist due to pitch error in the lead screw, backlash between the screw and the table, etc.

Incorrect movement of the table is not exposed by any automatic checking system; consequently, by the time the error is enough to be noticed by the operator, work can be spoiled, and possibly damage done to machine and cutter.

comments

To date (June, 1960) the three machines have aggregated some 9,600 hours running.

The first two machines have been refitted with hardened and ground lead screws, which incidentally increased the cross traverse from 11 in. to 15 in. The third machine was supplied in this condition.

The change points in the geometry of the cutter path are calculated, instead of those of the component profile; this can involve a little extra calculation. The points on the path must not be more than 2 in. apart, even though the contour is mathematically continuous and smaller spans are commonly used to obtain higher accuracy and better finish.

Considerable effort has been spent in reducing the inaccuracies arising from lead screw pitch error and backlash and in adjusting the table ways. The positional errors have been measured and reduced to the minimum possible by using the adjustment provided in the control. This is linear in form and as the errors are generally non-linear a compromise has to be struck. It is possible to apply compensation by modification of the programme data, but this precludes interchangeability of the machines.

The maximum errors arising are shown in the following chart:

	Lost Motion	Pitch Error
Machine 1		
	Longitudinal .0017 in.	.0064 in. 29 in. uncompen.
	Longitudinal .0017 in.	.0016 in. 29 in. compensated
	Transverse .0028 in.	.0006 in. 12 in. uncompen.
	Transverse .0028 in.	.0006 in. 12 in. uncompen.
Machine 2		
	Longitudinal .0010 in.	.0106 in. 29 in. uncompen.
	Longitudinal .0010 in.	.0022 in. 29 in. compensated
	Transverse .0022 in.	.0011 in. 12 in. uncompen.
Machine 3		
	Longitudinal .0009 in.	
	Longitudinal .0009 in.	.0013 in. compensated
	Transverse	.0016 in. uncompensated

In practice few components use the maximum travel of the slides, consequently it is possible to produce components within $\pm.003$ in.

The quality of surface finish has varied considerably; a reasonable standard is now achieved by frequent maintenance checks of motors, switch contacts, etc. By reprogramming with additional points between which the machine control interpolates, improvement can sometimes be obtained, but this is not desirable if it reduces the feed rate below that which the machine is physically capable of performing with a consequent increase in cycle time.

The punched paper programme tapes have been used in some instances for upwards of 200 cycles without deterioration causing error.

The percentage of machine availability varies and figures are given based on a period of three months:

	Machine No. 1	*Machine No.* 2	*Machine No.* 3
Year Ago ...	86	69	88
Now	75	34	90

Machine No. 3, which was delivered with hardened and ground lead screws and having two threads per inch as against four threads per inch in Nos. 1 and 2, has given less trouble than either of the earlier machines.

preventive maintenance

The electronically-controlled milling machine depends for its performance (after the proving of the programme) on the accuracy of the electrical control system and the standard and condition of the machine tool with which it is coupled. To ensure a satisfactory product it is necessary to maintain both these components to high standards, and this can only be done by routine maintenance.

Ferranti

To maintain a high rate of machine utilisation, the control system has been designed for rapid location and rectification of any faults, while a daily low voltage test has been devised to reveal any faulty components before breakdown actually occurs. This consists of a marginal test using simulators and a performance test using a special tape.

The marginal test is applied to each tier of trays in turn and consists of varying the screen voltage to all valves in that tier and noting the lowest meter reading at which the item just operates with complete reliability. If this lowest voltage exceeds a given figure, steps are taken to ascertain and rectify the cause.

The performance test checks the register system fault circuits and servo system, by running the special magnetic tape and noting the pulses recorded in the check channel monitor tube. Readings are also taken of the power supplies.

The daily routine check has been discontinued as now the operators have become so familiar with the pattern of signals shown by the console that they are able to recognise incorrect functioning.

In a monthly test, the ratemeters, phase-sensitive rectifiers and decoders are checked. To carry out these tests efficiently equipment recommended by the suppliers is used.

Machine maintenance is carried out by inspecting the level of oil in the servo-gearboxes and lubricating the leadscrews, machine slides and spindle daily or as required.

When faulty plug-in units (Fig. 22) are found, they are normally replaced from the stock of spare units held and returned to Ferranti Limited for repair.

E.M.I.

In a system which depends upon physical contacts for its positional information and reliability, regular maintenance of these units must be carried out.

The fortnightly check consists mainly of examining the brushes of the servo and blower motors and tachogenerators for wear and freedom of movement and cleaning their commutators.

The stores are tested by running a stores test tape through the reader. This ensures that all the relays in the store units are energised, stops being inserted to allow information to be read and their operation verified. A three-monthly check covers this and also checking the cleanliness of the 64-way analogue unit switches, the 128-way interpolator switches and the uniselectors.

Six-monthly checks include the servo and blower motors, the reader unit and static tests on the servo-amplifiers (balance), oscillator unit (output) and power supply units.

The analogue unit gearboxes are drained, flushed and refilled every 1,000 hours.

Apart from the normal spares holding of commutator brushes, relays and fuses, a spare store is carried. In the event of a store failure, this unit replaces the faulty store which can then be serviced, reducing breakdown time to a minimum.

To carry out these checks efficiently, test gear recommended by the suppliers is used.

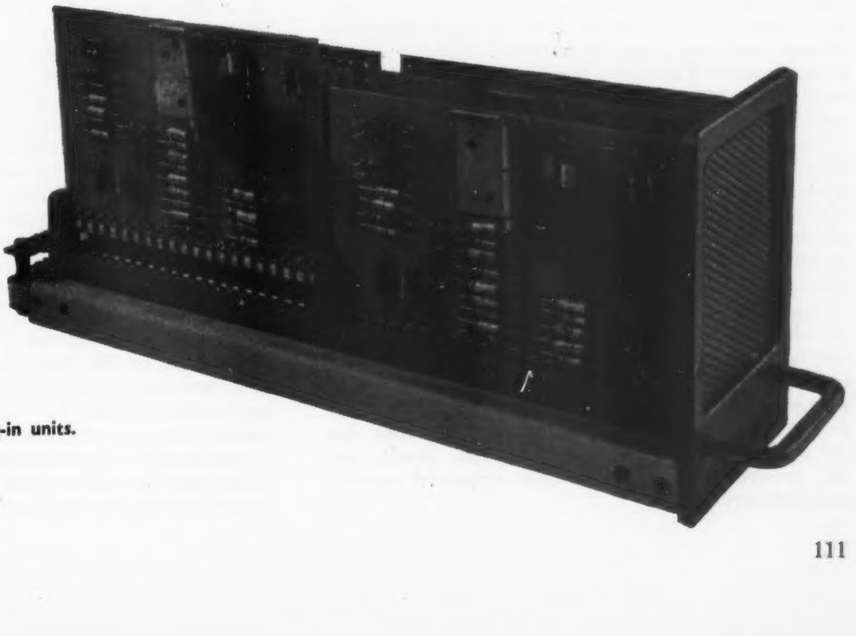


Fig. 22. Plug-in units.

Machine slide-ways are lubricated under the normal factory procedure, care being taken to ensure that an adequate supply of oil is always present.

other electronic controlled machine tools

The emphasis in this Paper has been given to describing the introduction and experience of Royal Ordnance Factories, Nottingham with electronically controlled profile milling machines. This factory possesses other machine tools which have received much less mention, either because they have been introduced more recently or their performance is neither so spectacular nor a great departure from conventional machine tools.

Newall Spacematic Jig Boring Machine

This jig boring machine has a measuring and control system designed by the British Thomson Houston Co. Ltd., which will position the table accurately in both horizontal directions. This automatic co-ordinate positioning is operated either by a punched card for programmed or cyclic work or by manually operated setting dials for individual operations.

The machine has been used for normal production work for nearly two years maintaining an accuracy of ± 0.0002 in. and has given every satisfaction.

Atlantic Co-ordinate Spacing Table

This is an electronic controlled co-ordinate spacing table used in conjunction with a radial drilling machine. The control equipment is designed by E.M.I. Ltd. and operated by a punched paper tape.

The machine and table have been delivered recently and no operational data is yet available.

Kearns' Electronically Controlled Boring Machine

This horizontal boring machine was designed and built to incorporate the B.T.H. measuring and control system and is operated either manually or by a punched card.

The machine has been installed recently and machining trials are being carried out, but it is too early to make any statements regarding performance.

CONCLUSION

The electronic control of machine motions to produce engineering profiles represents a distinct advance in practice which has come to stay and, in fact, must inevitably extend to a wider field of usage. This does not mean that work can be undertaken by these machines without careful consideration; it will be more necessary in the future than ever before to give detailed consideration before deciding to undertake production by one of the various methods available. This is essential if the best results are to be obtained from the machines and if unfavourable reports of their performance, due to incorrect application, are to be avoided. This often happened with innovations in the past, when ill-considered usage resulted in an entirely false assessment being made.

Equipment of this nature results only from considerable scientific and technical development on the part of the manufacturer; its introduction involves the user in almost as intensive an effort to ensure an understanding of the equipment, its proper usage and its effective application to the work. Manufacturing approaches may need to be re-fashioned and one's outlook on maintenance changed, and it will be many months before the possessor of such an equipment can be really *au fait* with it. Despite this, one should not view electronically-controlled machine tools as a new and different isolated piece of plant but rather as one step farther towards automation. In their day the shaft drive which replaced the lathe treadle and the powered self-act must have appeared equally revolutionary.

Not only can flexible and economic production be achieved for small quantities of components; other advantages also appear to be possible by thoughtful arrangement of these facilities. For instance, for the relatively small expense of the necessary tape an early supply of a critical component could be effected with the resultant ability to eliminate snags in design or assembly which, if found at a later date might cause a complete hold-up of production. Again, it would be possible to use the selfsame tape to produce the templates from which the main production would be made on normal copying machines. This sort of procedure could well justify the small additional expense if it avoided a serious bottleneck on assembly.

Some modification in the method of dimensioning drawings could be introduced with advantage. Drawings currently in use are not dimensioned in the most convenient form for use on these machines; this is no new problem as in the past the production of drilling jigs, fixtures, gauges, etc., by normal tool room and gauge shop methods has necessitated the calculation from the standard system of dimensioning of rectangular co-ordinates, and this work has imposed a heavy load either on the Drawing Office or has had to be done on the shop floor. As design frequently emanates from a series of co-ordinate points it should be possible to modify dimensioning to follow this pattern more closely. Careful consideration needs to be given when dimensioning certain features which in the past have been considered trivial and have no functional bearing on the design itself. For example,

when two angular lines have been blended with a radius to form concave contour, little thought has been given to the size of the blending radius. In conventional milling nothing worse than an unnecessary change of cutter is involved ; with the tape operating machines this problem becomes more severe, and in the case of the magnetic tape machine really complicated. It follows, therefore, that the utmost care is required in the detailed design of each component.

The machines which are installed at Royal Ordnance Factories, Nottingham were among the very first produced in this country and this was the factory's first experience of using this type of electronic equipment. Too much emphasis, therefore, should not be laid on small shortcomings either of the machine or the applications of the machines by the factory. Our efforts have added to our experience and production knowledge; manufacturers have now had the opportunity of seeing their equipment in use under exacting working conditions and so are enabled to eliminate minor defects in the design of the machines and to gain information to enable them to produce more advanced types.

The effective life of the electronically-controlled machine tool has been given considerable thought in many quarters. Whilst it would be wrong to be dogmatic in forming any conclusion, by considering the make-up of the equipment as

(a) machine tool, and

(b) electronic equipment

it would appear that the electrical components of (b) can be replaced from time to time easily and possibly not too expensively, and in consequence the life period of the whole equipment is that of the machine tool itself. More frequent overhaul might be necessary to maintain high precision throughout the machine's life, but the extra effort expended in so doing is really used in maintaining a machine to a higher standard than that to which its long usage would normally reduce it.

As with any other instrument the ultimate accuracy of the product is seldom that of its measuring unit. The normal acceptable machine tool tolerances can produce a deviation from the expected dimension several times greater than the smallest unit of the measuring scale. In the magnetic tape machines most of the mechanical linkage has been removed from the measuring devices; thus, improvement in accuracy of the product will depend upon machine tools being manufactured to closer tolerances, which may not be justified, either by the higher capital cost or the more difficult maintenance problem.

An extension of profiling under electronic control both within and without the field of milling is now evident in its early stages, but will definitely be established in a few years from now. In the more distant future one can foresee the preparation of component producing data tapes by appropriately programmed electronic digital computer, direct from an input of the mathematical statement of the design requirement. Already machine tools are being made to flame-cut ship plates to contour under electronic control, and the obvious step forward from this point is the deriving of the plate contours by computer from the mathematical expression of the hull form.

Consideration is being given to inspection of profiles by directing a stylus around the component contour by the magnetic tape control and observing (or possibly recording) departures from plan. At first sight the idea commends itself, in that it avoids the cost of expensive gauging equipment or an elaborate gauging set-up with standard equipment, and must be quicker when one or a few components only are required. In such instances the procedure might be acceptable; however, there are two basic objections. Firstly, the positional accuracy which can be achieved *via* the control gear and the machine tool elements is inadequate for precision measurement; and, secondly, it could be considered bad engineering practice to use for measurement a robust machine tool designed for heavy stock removal.

Since the introduction of the digital electronic computer, Service Centres are being opened in many of the larger towns, and shortly it should be possible to hire computer time or to have computer work done, at a local computing centre. This should do away with the long return journey between factory and computer and the risk of loss or delay. With a factory programmer trained to use a simple Autocode, it is within the realms of possibility that the calculation of the co-ordinates of the component could be done in the computer immediately prior to the preparation of the control tape.

Perhaps in the years to come machines under distant computer control will produce, inspect, assemble and package work without human intervention, all in accordance with a simple input statement of requirements.

In conclusion, the writer wishes to record that this equipment is under the direction and control of the Superintendent of the Royal Ordnance Factory, Nottingham, whose staff have been responsible for its introduction, its operation and for the collection and preparation of the considerable volume of data which has made possible the presentation of this Paper.

The Joint Discussion on this and the subsequent film and commentary given by Mr. Blades, commences on page 116.

THE APPLICATION OF CONTROL SYSTEMS TO QUANTITY PRODUCTION – INSPECTION CONTROL

illustrated by film and commentary given

by R. L. BLADES

Assistant Chief Inspector,
Vauxhall Motors Ltd.

THE subject matter of the film to be shown almost entirely refers to the quality of components produced in high volume, and measured by the use of gauges and gauging devices, both manual and automatic, and also by the use of Statistical Quality Control.

The subject under discussion will be confined to the high volume production of motor car gear boxes, engines, hypoid rear axles and all the major components and assemblies in a motor car.

You will, therefore, have gathered by this time that the Paper is concerned with the technique and economics of inspection, rather than in the control of the machine tool itself.

Our machine tools are mainly of the orthodox type which are now in use by many companies, i.e., in-line transfer machines, multi-wheel grinders, high speed hobbers, vertical automatics, etc.

These machines produce in much higher volume and at feeds and speeds in excess of those which were commonly in use a few years ago, and the first objective of this Paper is to show in a simple form some examples of how we control quality by measurement of the component to the engineering specification.

You will see in the opening shots of the film a picture of our basic standard measuring slip gauges, which are guaranteed and certified by the National Physical Laboratory as being a set of slip gauges with a maximum error of three millionths of an inch. The whole of our gauging system is related to these standards, and the system is controlled by a group of inspectors who patrol the machine shops and check the fine limit gauges in use by both production operators and inspection alike, every shift.

Probably the most simple and reliable system of measurement which we use is through the medium of the low pressure air gauge. We use these gauges for measuring both internal and external diameters for size, taper and ovality, and in view of the sensitivity of these gauges we realise the importance of the design of the machine tool, and that it must be sufficiently rigid and accurate to repeat itself to fine limits, in order to satisfy the demands of these gauges. They vary from 2,500 - 10,000 magnifications in range and are in use throughout all our engine, gear box and hypoid axle manufacturing systems.

automatic inspection

You will see one or two interesting shots in the film of the automatic inspection of crankshafts. This machine checks 41 dimensions on the journals and crank pins, and is capable of inspecting 40 crankshafts per hour.

Another device which you will see is an automatic diamond hardness tester for checking the surface hardness of gudgeon pins. This machine is hopper fed, is completely automatic and will operate without any attention until the hopper is empty.

It is extremely sensitive and will reject soft pins within the tolerance of one Rockwell "C" point.

The automatic crankshaft inspection machine that I have just described is by Sigma and another interesting piece of equipment by the same Company is the inlet and exhaust valve measuring machine which itself is capable of inspecting nine dimensions at the rate of 800 valves per hour.

statistical quality control

We also use a simple system of Quality Control on certain machines which warn tool setters that the component is approaching either the top limit or the low limit of drawing. From hour to hour during the day, and before the part is allowed to reach these maximum tolerances, cutting tools are reground and reset, and the part brought back to approximately the mean dimension again. This ensures almost constant accuracy of the part and reduces scrap to a minimum. Much more could be said to describe these operations, but at this stage we ought to have a look at the film and I will describe some of the operations which you will see as the film progresses.

Largely as a result of the invention and development of the motor car the machine tool industry has, since the early part of this century, steadily but progressively revolutionised the method of machining components both in higher volume and at lower cost.

The development of automatic devices such as transfer mechanisms has demanded more and more accuracy, not only in the machine tools but in the consistency of casting and forging shapes in components. The increasingly high volumes which these machines will produce has also stimulated the design and development of faster and more accurate measuring devices. In spite of the present efficiency of modern measuring equipment, however, there is still a long way to go in the reduction of inspection costs.

We are aware that production and tool engineers in many places are looking at the possibility of equipping machine tools with electronic, hydraulic and mechanical devices to stop the machine when dimensions exceed the engineering tolerances, and if this were possible it could be quite a step forward in the economic production of accurate machined parts. We have all seen examples of automatic inspection machines but in the writer's estimation there are not nearly enough of them nor are we progressing fast enough in this direction.

cost reduction

We are of the opinion that the recent progress which has been made in the productivity of the machine tool and which we all know has been a tremendous leap forward in the past few years, cannot be expected to continue at the same rate, and that it may be that we must be satisfied with these highly productive machines for some years to come. It does, however, give us an opportunity to catch up with this rapid progress of the machine tool by doing the same thing with automatic inspection machines and we feel that such a drive would produce some useful reductions in costs in the industry, especially inspection costs.

We are quite aware that some of the automatic measuring machines will be very costly, and we are not at all interested in spending money for the sake of spending it, but we are quite convinced that a reduction in the cost of the product could be obtained by reducing inspection costs through the medium of such machines as these.

So long as we adhere rigidly to this principle of a reduction in cost resulting from extended use of such equipment, there must be a rich field of exploration open to the technical and scientific bodies in this country.

We have heard much about these extremely clever machines which are controlled by information from punched tape feeding computers and it would be interesting to hear of any trend in this respect with automatic inspection devices, and whether it will be possible automatically to measure components in high volume to fine limits by these means in the future.

We would have thought if it is now possible to control the path of a cutter to tolerances of .0002 in., that it would also be possible to devise equipment that would measure components to these dimensions by the same means.

non-destructive testing

Machine tool efficiency and quality standards are also reflected in the condition of castings and forgings in relation to cracks, porosity and laminations, and it is just as necessary to find ways and means of eliminating these faulty components before they have a chance to destroy expensive cutting tools, as it is to devise machines which will automatically inspect components for size.

It seems to us that the solution may lie in the eventual development of automatic ultrasonic equipment which will detect these cavities and cracks before they arrive at the machining stage.

Finally, these remarks are deliberately intended to be provocative, so that in the discussions which will ensue, we may learn something of the trends which we hope are taking place in the solution of these problems so that we can at least be sure that we are using the best equipment which is available.

THE JOINT DISCUSSION REPORT commences overleaf

JOINT DISCUSSION

Chairman: Mr. K. J. Hume, M.I.Prod.E.

The **Chairman,** opening the discussion, said that the slip gauges shown at the beginning of the film had been described as being within 0.000003 in. He felt sure that when the slips were used as standards they were not assumed to be correct, although some of them might be within 0.000003 in.

Mr. C. F. Steventon (*Development Engineer, British Oxygen Gases Ltd.*) referring to the development of new methods of programming, mentioned by Mr. Pull, showed a number of slides concerned with one of these methods. When applying the Ferranti control system to an oxygen cutting machine, particularly for use in the ship-building industry, it had been found that the existing methods of programming were not satisfactory. The need to specify the co-ordinates of all the change points of a profile could not be met in the shipyards.

Mr. M. Seaman said that the system described emphasised the connection between the designer and the actual machines at his disposal. A designer could inject a tremendous amount of overhead if he did not realise the true potential of the machines. One had to build rapidly a complete system. The designer, as Mr. Steventon had shown, had a completely logical three-dimension to two-dimension process, with direct machine control and a high degree of accuracy conditioned only by the functional accuracy of the machine and self-inspected by the regulating processes of the computer, the machine and the piece produced. He could insert a visual programming point immediately before the computer.

On the side of economies, the designer must understand the potentialities of the equipment. For instance, in the ship-building case one could nest plates, and put in a number of small parts so that the scrap figure remained low. Also, the length of cut in terms of total machine time produced a high degree of efficiency. If the designer cut all the components contiguously he had a progress element coming into the design which was of great value in giving high through-put and utilisation, as well as being very efficient in the production of parts with low distortion. At this point a certain amount of random selection occurred. It was vital.

One of the human necessities of a completely numerical series was a visual point of flexibility and control. There was no mathematical solution to the maximum utilisation of the sheet. One fitted this in visually after a high speed drawing had been made. One then had all the major co-ordinates and the polar shift of the part and the whole thing became obvious from a progressive point of view.

The designer could select from a number of shapes. If he drew the design freehand he injected a 30% increase in overhead. If he selected a shape described numerically, his part was finished perfectly and self-inspected. He went from programming straight to the computer. Here one had design, manufacture and the product coming together.

In this case the problem was mainly two-dimensional, but it was quite obvious that the situation described could apply in all our systems, and represented the biggest nut one had to crack in the development in this field.

Mr. A. Dobson (*Methods Engineer, R.O.F.*) asked what Mr. Pull now considered to be the practical complement of controlled machine tools for the Nottingham factory, based on the experience gained on the magnetic tape controlled machine, the punched tape controlled machine and the Spacematic. Which type, and what number of each type did he consider to be justifiable and necessary?

Mr. Pull said that one's predictions about requirements in machine tools were governed by one's ability to read the crystal ball. For that reason they endeavoured to keep a broad kit of equipment in order to be able to handle anything that came along. In addition to the usual machine tools they had specialist machines.

The machines at Nottingham were among the very first of the electronic equipment installed in the country. The desired accuracy of components had not been achieved on every occasion. The paper tape controlled machine had advantages that the magnetic tape machine had not. He could not conceive anyone building a factory in which the grindery had tool room grinders only.

The paper tape machine was no longer being made in the same form but with a new system of measurement which produced greater accuracy, and the machine had advantages of cutter adjustment not possessed by the magnetic tape machine, which was essential if one were to get the utmost out of the machine. In batch production one did encounter variations. Hand-forging contributed to this as the amount of material left on varied. One needed, right at the operating point, to be able to take another cut when necessary. Broadly one had to select the machine tools according to the type of work being done.

Mr. J. B. Bullard (*R.O.F., Nottingham*) said, in answer to a question by Mr. G. Walters, that they had not had a great deal of trouble, so far as maintenance and breakdown was concerned, with the

Ferranti. Fault detection was assisted by the use of parts recommended by the manufacturers. They used an oscilloscope to get to the source of the trouble, and the use of plug-in units quickly got the machine back into action. Delay occurred only if a major component failed.

They had three E.M.I. machines. The fault detection system was not so advanced, but they were able to transfer suspected faulty units from one machine to the other. If the fault also transferred they had, of course, found the part that needed attention. In the first of the E.M.I. machines, in which the lead screws had been replaced by hardened and ground screws, the desired accuracy and finish had not been produced; at the moment, however, they were running well.

Mr. F. Roberts (*U.K.A.E.A.*) said that Mr. Pull had mentioned, but not emphasised, the comparative cheapness of the one-off job with the tape machine. He deplored the way in which the big motor trade manufacturers dealt with the machine tool manufacturer, swamping him with orders to the detriment of the smaller man and wanting a good deal for their money. Other people had to pay for this.

Mr. Blades said that during 1955 - 1956, he had had the problem of purchasing several million pounds' worth of machine tools during their expansion programme. The leading machine tool manufacturers were able to supply transfer machines but not all that were required, largely because the whole programme had to be completed within a period of 15 months and they therefore had to find other sources of supply. On behalf of the machine tool manufacturers, he would mention that they had made it clear that they valued the business of the smaller firms with whom they had been associated over many years and they could therefore offer to reserve factory space up to a given percentage, if the customer was willing to accept it, and guarantee to fill it, with the reservation that they must fulfill their obligations to their other customers.

The money spent in England was, therefore, only a part of the major project and it had taken 15 - 18 months to obtain the tools. For these reasons, he doubted whether they had contributed to any delay Mr. Roberts might have suffered in this respect.

Mr. N. Beardsworth (*Sales Promotion Officer, Rotax Ltd.*) said that Mr. Pull had referred to a discrepancy between the actual and the real position arising from lead screw errors. Mr. Bullard had implied that the errors were less sizable after refitting with hardened and ground lead screws. Would Mr. Bullard confirm that he found no deterioration due to wear on the anti-friction type of screw shaft?

Mr. Bullard replied that, since fitting the new hardened and ground lead screws they had noted no obvious deterioration or wear on the screws. While the machines were producing components as near to correct as they wanted them, they accepted the screws as they stood (no programming corrections being attempted).

Mr. J. M. Jotcham (*S. Smith & Sons (England) Ltd.*) said that, as an electronic engineer, he could not understand the necessity for complicated and expensive computer installations in the circumstances they had been discussing. The installations cost from £13,000 to £500,000. A combination of analogue and digital techniques could quite easily provide a considerable and cheap service. In many cases the problem was one of co-ordinate conversion.

Mr. Pull said that R.O.F. work for the Ferranti machine was processed on a computer held by that organisation. Various computer centres were opening up, including those of English Electric and I.C.T. The cost of a machine capable of converting a No. 3 Cincinnati milling machine was about £5,000 per motion, that is for two motions about £10,000, while the actual computer work done might cost only a few pounds.

Too many drawings bore the translation of a designer's requirements into something that he thought could be made. If one could examine the mathematical requirement first, and translate it through a computer into co-ordinates one could avoid the intermediate steps.

Mr. Jotcham said that a minor computer problem was involved and the installation to deal with it need not be that found in a computer centre: it could be in the drawing office.

Mr. K. H. Jenkins (*Machine Tool Engineer, Bristol Siddeley Engines*) felt that in the light engineering field one did not find many jobs that require computer service, the exception being certain forms of three-dimensional contouring work. His own firm had installed a two-dimensional tape-controlled contour milling machine which did not require computer service. His firm also possessed a general purpose computer which it used for aerodynamic calculations, and although it was not a tape producing machine it could, if necessary, produce the co-ordinates and other information from which a Ferranti type magnetic tape could be made.

Three years ago the Director of a well-known machine tool firm said, at an S.B.A.C. meeting, that outside the aircraft industry there was little use for tape-controlled machines. At that time he had been inclined to agree, but the ultimate potential of tape control was not for the production of two- or three-dimensional shapes, but rather the means of servo-control of all functions of machines. At the recent Machine Tool Exhibition they had seen examples of this in the Milwaukeematic and, possibly, the Archdale Autonomic.

This was the real need in industry and one did not have to possess a computer to operate such machines and mechanisms. All that was required was the knowledge of some form of simple binary coding system and a simple tape punching machine (not a

computer). Then the programming of the work and the preparation of the tape could be accomplished in one's own office. In this respect tape control could affect industry as a whole. Many thought of punched tape and card control as systems requiring complicated electronic equipment exclusively, but this was not so. There were systems which functioned by purely electrical means, tape controlled co-ordinate table positioning, for instance. One thought of magnetic tape for contour machining complex three- or possibly two-dimensional toolroom type work.

He only wished that turbine engine designers could agree with Mr. Seaman that a two-dimensional shape could be produced for a three-dimensional product. In turbine and compressor blade design, designers lined up co-ordinate points by sight and by hand so the shape could be anything. Mr. Seaman had said: "We can state a simple law which governs that shape, therefore we can compute it." If turbine blade designers could do the same with turbine and compressor blades, the production engineer's lot would be far easier.

Mr. Large (*Ferranti Ltd.*) shared Mr. Jenkins' enthusiasm for the Milwaukeematic, but of the 87 such units sold every one was being programmed through a general-purpose computer. Their theory in the early stages had been that the control system on the shop floor should comprise solely a servo. This meant easily maintainable equipment and straightforward reproduction of what a computer produced. However, it could obviously produce only straight lines in the absence of calculating or interpolating equipment, so it had to be backed by a computer. Their first machines had been in the field now for five years and had gone in under this restricted utilisation policy. Turbine blade machining was not then thought possible but today the same machine was merrily churning them out. They were selling equipment which moved the machine to predetermined dimensions, on computer information. One could not do development work on machines already sold but could extend their scope continuously with new computer techniques. This was why they had continued with the computer.

The ship-building work described was an example of the development of programming on computers. They were also taking a different line of attack, by which they could do very much more work on the machines in regard to three-dimensional shapes, which were easily computed. This was a long-term programme and directed mainly at the motor car industry, which contained all the problems in the die sinking field that were common to general engineering. It could not be done without the aid of a computer.

The **Chairman** said he detected some objection on the part of the purely electronics engineers to the use of highly complicated and expensive machines for the rather ulterior motives of production. If the Royal Ordnance Factory, or any company using machine tools found it economic to buy computer time, or even a computer, that ought to be good enough. He felt that engineers generally should realise that the research and design engineers had not a monopoly, and that all problems put to a computer had not necessarily to be highly abstruse. If it saved a lot of people a lot of time, it was well worthwhile.

Mr. Seaman said that he thought a model of the economic approach to the computer was missing, and this was perhaps at the opposite pole to the present argument. Where the electronics engineers went wrong, in looking askance at computers, was that once you had a system which was numerically and logically within the framework of a completely integrated system, the computer made it possible to really attack overheads. Moreover, the resulting combination of machines on the shop floor made possible a gross through-put density representing maximum utilisation.

He had been delighted at the emphasis placed by Professor Loxham on inspection on the shop floor as a direct power of the craftsman and the machine and process operator; also the aspect of high utilisation. This was the technical focus of the problem. If the density of through-put were 1, a logical system, introduced in even an efficient organisation, would carry it as high possibly as 1.2, expressed in pounds of output per sq. ft. and per £1 of capital invested. In the ship-building case it was 1.5 or 2.

With computers, one had a possible saving of 10% in gross cost, and a possible increase in through-put of 20%. The designer, of course, injected the basis of the overhead, and could be responsible for great savings. Further economies could be effected by avoiding what were virtually fixed management decisions running round in a "rat cage" year after year, without the slightest effect on the product, but continuously increasing its cost.

The breed of machine and of control was important. For the small group of factories, one computer servicing several was an obvious procedure to adopt. The trend of designs would be of just as much importance to the small and the batch manufacturer as to the larger organisation. The important thing was to consider costs in the light of the whole model, and not simply at the machine.

Mr. D. Foster said that Mr. Blades had described very well indeed the present state of the art of automatic inspection in the progressive factory. He had really thrown out a major challenge to the electronics industry to produce any new tricks in the field of automatic inspection.

It was interesting to know that in Russia, while the "back-room" boys were talking about self-optimising computers, the commercial people were only interested in buying from the West automatic inspection equipment. This was the real issue for industry, and was associated with the trend to make things quickly and well.

The Russians were perhaps level with Britain in this field, but in the United States, and particularly in the Detroit area, one found a partial answer to Mr. Blades' query: "Where do we go from here?" The U.S. had introduced electronic techniques operating at much higher speeds than our own: the usual rate of inspection was 3,000 or 4,000 parts per hour. However, the cost of the machines was perhaps five times greater and one had to have a project which would justify inspection at such a fast rate. The break-even point was about 2,000,000 parts a year.

It was surprising that the electronics industry had done so little in the tremendous field of automatic inspection. He felt, however, that millions would be spent in it in the next 5 to 10 years. Electronics was, of course, the science of handling wave forms and could not help unless the problem was one which lent itself to the "jiggling" of electrons. Electronics would enter the field when it could find a wave form trick of dealing with dimensional and shape inspection.

Two developments were of interest: the ability, by means of light interception systems, to inspect the product without stopping manufacture; and precision inspection for shape by the use of cathode ray techniques. These were likely to be brought into the open and adopted in the next two or three years. Any development must, of course, be economic.

Mr. Pull said that, unfortunately, these days the term "computer" was all things to all men. The computer built into, say, the E.M.I. machine used by R.O.F. was not a general purpose electronic digital computer. Its task was mainly to work out intermediate co-ordinates. So far as inspection was concerned, they had considered putting up a stylus and running around the component to see whether it was possible to make a measure of deviation from plan after manufacture. He had given, in the Paper, two reasons why this did not seem very practical. Another was that the rate of traverse was much too slow: one needed to be able to "walk" a floating head round it in a matter of seconds. No doubt their present efforts would seem amusing in a few years time but the only way to progress seemed to be to experiment. They had done this with electronic machine tools, and had found some value and advantage in them. He thought they would come in greater variety, and were here to stay.

Mr. Bullard said that, as mentioned by Mr. Pull, R.O.F., Nottingham had experienced difficulty with the E.M.I. machine at first, owing to lost motion upon reversal of the screw, i.e., the table; also minor difficulty associated with the use of the cutter compensation unit. He showed several slides to illustrate these, and methods adopted to overcome them.

Mr. L. G. Carver (*Production Engineer, Bristol Aerojet Ltd.*) stated that, like most of the members, he had come to the Symposium to learn something about control systems in relation to machine tools. Latterly, they seemed to be hearing only about computer control systems, and little else. Were they, in fact, being invited to purchase a "gold brick?" Mr. Jotcham had raised the question of the necessity or advisability of the introduction of computer control systems as against other methods of control in general engineering work, especially in relation to the problems of the small jobbing shop. In putting his question, which did not appear to have been answered, Mr. Jotcham had also invited comment from the body of the hall. Mr. Seaman's drawings, though effective, seemed to provide a closed loop with no triggering action.

Would it not be possible for the question to receive further consideration and comment?

Mr. Pull replied that he had been asked to give R.O.F.'s experience of electronically controlled machine tools in jobbing and batch production. Vauxhall's were to do likewise for the large-scale user. He had done as asked but would not care to specify that a firm should have this or that type of machine. In the aircraft industry, where three-dimensional contours were involved, the machines were paying for themselves handsomely. R.O.F. had, in a number of instances got a cheaper component—in some cases markedly so. The work had almost always been done more quickly, and in jobbing and batch production this was very desirable.

Firms working to a lower degree of accuracy might not need them at all but they had been shown in use for the flame cutting of plates, where the tolerances are very much greater than any the R.O.F. worked to. The desirability of using such equipment had to be considered in the light of the product and the quantities to be made. R.O.F. had begun examining the matter in 1956 and had not bought the machines until 1958. It was very pleasant to be able to say that they had proved worthwhile.

Mr. L. J. Blache (*Elliott Bros (London) Ltd.*) asked why there had been such delay in introducing the three-dimensional machine, which Cincinnati had been developing more than 10 years ago. America had had electronic computers for more than 15 years. Had the machine tool industry simply not reacted to the obvious need of the aircraft and automobile industries for this type of equipment?

Would it be possible to avoid the high expense of storing, producing, interpreting and converting information, by using a diagram or drawing in the case of two-dimensional cutting — where the drawing itself was black and the surrounding portion white — with a simple read-off unit of the kind found on differential analysers, to convert the information directly from the drawing board to the machine tool?

The film shown by Mr. Blades seemed to indicate a high proportion of time spent on workpiece manipulation by the operator. The inspectors, especially, seemed to carry out simple measuring operations in a time-consuming manner. Would analysis of these, in order to develop workpiece manipulators and otherwise reduce the time taken, prove profitable before embarking upon fully automatic measuring?

Mr. Pull replied that one reason for the apparently slow development was that sometimes the emphasis across the water was on what might be done rather than what was being done.Several visits in recent years of officials of the R.O.F's. had been made to the United States to look at computers used for data processing and production control. They had found nothing that they could use. A few cards were being scheduled at the input end, but little was being done about real production control. Two of his colleagues had recently toured the United States for a month. They had visited I.B.M. at Poughkeepsie, among other firms, and had returned with the same story. In Britain, a little had been done by I.C.T. at Letchworth to integrate the passage of work through its many operations and put it into its correct position in relation to the flow of work from the shop. There were obvious difficulties to be overcome, including the size of the machinery and the task of gathering all the necessary data.

One R.O.F. had been conducting an experiment in scheduling the passage of work through a factory on a computer, but nothing was being done on a large-scale yet. The computer was not, of course, very " old " yet.

Mr. Blache's suggestion was followed in certain cases, e.g., with flame cutting where the degree of accuracy was not great, but often the tolerance was less than 0.001 in. and here it would not be practicable.

Mr. Blache added that Mr. Pull had described the great satisfaction that he had had with the machines. Such things were not sufficiently well-known.

Mr. Jenkins felt it was important to specify exactly what one meant in speaking of three-dimensional machining. Much of the work was done in one or two dimensions with scanning in the the third.

Three-dimensional machining could be done directly from the drawing board, as in the case of the Contouria which produced turbine blades in this way. One had to have a drawing for every path of the cutter. Also, with the aid of a computer one could plot and draw paths as near together as a few thousandths of an inch and be left with very little work to do afterwards.

Mr. Jotcham felt that Mr. Pull might be more on his side, in this matter of needing a large computer for the two-dimensional problem, if he put the case in another way. It should be possible to undertake vital work, involving co-ordinate positioning of tools or tables, using predetermined curves or interpolation routines between any number of points, on machines which, by virtue of cost and operational characteristics, would fit into the drawing office. It would depend on the type of problem to be dealt with.

Secondly, the draughtsman could very easily design directly the programme for these machines, though he might have to break up the programme into a number of steps according to the eventual complexity of the complete profile.

Mr. Pull said that the use of the word "computer" might have created a certain amount of confusion. The digital computer was used, in the case of the Ferranti equipment, to produce a programme which gave a number of discrete steps to actuate the process. This information was recorded on a magnetic tape. The " playing " machine was a much cheaper device. It gave effect to those steps in keeping the machine moving in two (or three) dimensions. E.M.I. interpolated 1,600 intermediate positions between any two points nominated from calculation in the drawing office, as Mr. Jotcham suggested. The interpolation was done in the local electronic calculating device as the tape passed through, so one had something in the nature of a little specialised computer in the E.M.I. machine. The purchase of further expensive equipment was not involved.

In reply to a question on the time taken to inspect gears, **Mr. Blades** did not believe that the application of time and motion study would lessen the time which had to be spent by the inspectors on the measuring and checking of pistons, gears, etc., as seen in the Vauxhall film.

It should be borne in mind when looking at this film that most of the inspection operations being performed were critical examinations of " first-off " samples and in an operation such as this, time was not the most important element.

For instance, referring to that point of the film which showed gears being critically inspected, the involute curve, the run-out on the pitch line, the helix angle and the adjacent tooth spacing were extremely important and a little time and trouble taken to ensure that these dimensions were within the engineering specification, might well prevent expensive scrap being made and certainly did much to ensure the smooth running of the gears themselves. These errors could accrue from a machine tool which needed maintenance adjustment or from a faulty hob or gear shaping cutter. He need hardly add that gears were very expensive to produce, and therefore errors outside of the drawing tolerances should be shown up by critical examination during manufacture, and this kind of inspection was surely not a suitable subject for time study.

On the other hand, they had seen engine valves being inspected in high volume. They had nine dimensions, each to a fine limit, and one operator was putting through 800 an hour. He did not know any organisation that was doing such work any faster than this, but he would be interested to know it it were possible. The Sigma crankshaft machine dealt with 40 crankshafts per hour each with 41 dimensions, to fine limits. It was 90% automatic. The inspector could see at a glance, with the aid of the high magnification of air gauges, whether each dimension was within the engineering specification. The machine was both highly productive and accurately repeatable by virtue of the well-designed pneumatic and electrical relay devices it contained. He was of the opinion that 800 valves an hour, and 40 crankshafts an hour, was not good enough. He hoped to have an opportunity to say how he would like to improve these

figures, and to extend automatic inspection to many other components.

Mr. D. Blakesley said that he had been slightly involved in the design of a machine tool control system and would like to say a few words in defence of the maligned computer. In regard to the control system at the machine tool end, it was highly desirable to use, at some stage, a binary device. It may be decimal encoded, but was nevertheless binary and, almost certainly in these days, transistorised. This implied a digital device. The information on the drawing was basically analogue and at some stage one had to convert from analogue to digital information.

So far in the discussion they had talked almost exclusively about profiling machines — either millers or flame cutters. In these circumstances a general purpose computer was, he would suggest, the right way to convert from analogue to digital information. He was sure one could build a computer to go in the drawing office and do the job. Perhaps computer was not a good word to use. One had to remember that the sale of this type of machine was exceedingly limited. The firms concerned seemed to have been disappointed with their sales, and the development of a special computer was not a proposition at the moment. This was doubtless the reason why a very expensive general purpose computer was usually employed.

On the question of automatic inspecting machines, the cost of developing a mechanical machine was very high, especially if it was a one-off job. Now it was suggested that an electronic device might be added, and the cost of developing these was notoriously high. For these reasons, it was out of the question on economic grounds.

Mr. Blades, summing up, said that he felt a little like the employee who had gone into the office of the boss seeking a rise and had come out with a copy of Epictetus under his arm. He had not got what he came for, but he had received some consolation nevertheless.

He had been impressed by Mr. Steventon's and Mr. Seaman's blackboard work illustrating computer control from simplicity of design plus machine tool control plus feed-back inspection. That was the way he would like to do it, incorporating in the machine tool the ability to handle components of sound and simple design, and applying the automatic principle, whether by electronics, hydraulics or electrical relay, or all three. Mr. Seaman's statement that this was now a practical possibility for some firms seemed to give hope for the future.

In the meantime one was obliged to use a method of controlling quality off the machine—and in this way really controlling the machine itself—that was time-consuming, wasteful in floor space and involved a high percentage of the human factor, which was universally not completely reliable. From what they heard of the trends in other countries it would seem that the ultimate objective of high volume production practice was simplicity of design, machine tool control and automatic feed-back inspection, or alternatively, fully automatic inspection, wherever possible.

The capital so far invested on automatic inspection equipment had given a very satisfactory return. In under two years the machines had paid for themselves. He had seen, some years ago, electronic computers used in the milling of the profile of a very intricate jig and had recently learned that a colleague in the north of England, who represented a famous motor car firm, was currently buying a computer controlled machine for positioning and drilling holes. He was sure that the confidence placed in this computer-controlled drilling machine was fully justified but he was not so sure that the same confidence could be placed in a computer-controlled milling operation because of the hazard presented by deflection caused by cutter wear.

If it was not possible to get machine tool control and feed-back inspection all in one operation the alternative would be to capitalise on many more inspection machines which it was already known could do the work far more economically, accurately and consistently than by existing methods in general use.

He had hoped to learn how the work of inspection could be done more effectively, but had had to be content with the conviction that a good deal was being done to develop automatic motion for machine tools and automatic measuring equipment by the use of electronic computers. No doubt this effort would one day pay dividends. His only regret was that he had not at this meeting solved his problem of automatic high volume inspection by these means.

The **Chairman** said that as it was now 3.10 p.m. they had perhaps better bring the discussion to a close. He had no doubt that if they did not it would continue all afternoon! It only remained for him to thank the speakers for their excellent Papers and the great food for thought that they had provided.

The Paper presented in Session III, together with a report of the subsequent discussion, commences overleaf.

ECONOMICS OF CUTTING PROCESSES

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SOME literary licence has been taken in the interpretation of the title of this Paper and there is included a short section on the economics of automatically controlled machines which precedes the general topic of the economics of cutting processes.

The introduction of automatically controlled machines has undoubtedly focused attention on efficient cutting, since it is obviously inadequate to provide a machine capable of obeying complex instructions and to leave the vital cutting conditions to be set arbitrarily by the operator.

Whilst in many cases the automatically controlled machines can justify their purchase by comparison with existing machines, nevertheless, it is incumbent on production engineers to ensure that the high capital expenditure on automatically controlled machines is recouped as expeditiously as possible and that the machines are operating under optimum conditions.

It may be true that the machinability data to enable prediction of optimum performance is not yet ready to hand, but a concentrated effort over a year or so could well provide much valuable information.

economics of automatically controlled machine tools

Whilst automatic controls may be applied to a wide variety of machines, the two major applications are co-ordinate positioning and continuous profiling; hence the examples for economic analysis will be drawn from each of these.

It is not possible to generalise on the economic application of automatically controlled machines and each proposed application must be individually assessed.

However, the examples chosen are considered typical and serve to illustrate the main factors to be observed.

co-ordinate positioning

The example chosen is taken from an actual case which has already been described in the technical literature. In this, a frame of welded construction, as shown in Fig. 1, required six holes to be drilled and counterbored, nine holes drilled and tapped and eleven holes drilled, all operations carried out on a horizontal borer. The previous time on a conventional borer was 4 hours 34 minutes and the time on an automatically controlled machine was 2 hours 17 minutes.

The automatic machine uses punched cards to control co-ordinate settings. The operating cost per annum for each machine would be assessed approximately as follows:

	Automatically Controlled Borer		*Conventional Borer*
	£		£
Cost	25,000		12,000
Depreciation per annum	2,500		1,200
Insurance	50		20
Power	60		60
Heating, lighting	30		15
Maintenance	200		25
Operator	750		750
Supervision	75		75
National Health	35		35
Employee services	40		40
TOTAL	£3,740		£2,220
Utilisation at 80%	1,600 (hrs.)	at 90%	1,800 (hrs.)
Cost per hour	46/6d.		24/9d.

The total cost per piece would then be:

	Automatically Controlled Borer		*Conventional Borer*
Card punching:			
½ hr. at 5/- per hr.	2/6		
Loading & unloading:			
10 mins. at 46/6	7/9	10 mins. at 24/9	4/1½
Machining:			
2 hrs. 17 mins. at 46/6	106/2	4 hrs. 34 mins. at 24/9	113/-
TOTAL Cost per piece	116/5		117/1½

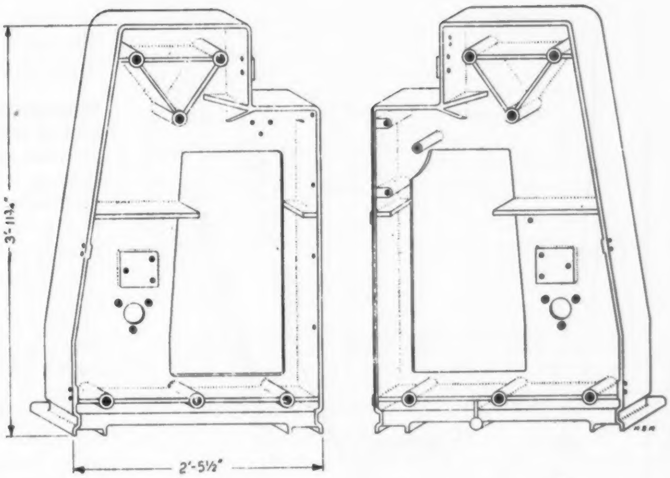

Fig. 1. Frames of welded construction.

In the above example, the total cost for one off is approximately the same for each type of machine. Any increase in quantity would spread the costs of card preparation, thus making the automatic machine slightly more economical. The major factors affecting the economics, apart from initial cost, are machine utilisation and loading time.

If machine utilisation is better than 80% in the case of the automatic machine, then the cost per hour will be reduced. Loading and unloading time carries full rate per hour, hence, sub-tables should be used where possible, to reduce change-over time.

The advantages of automatic control would be the reduced risk of scrap and the reduction of learning time on subsequent batches.

continuous cutting

This example is also from an actual case which has been described in the technical literature. A finger cam, as illustrated in Fig. 2, required complete machining except for the holes.

On a conventional miller the time taken was $5\frac{3}{4}$ hours, whilst on the automatically controlled miller the time taken was 30 minutes.

The operating cost per annum for each machine would be assessed approximately as follows:

	Automatically Controlled Miller £	*Conventional Miller* £
Cost	17,000	5,000
Depreciation per annum	1,700	500
Insurance	30	5
Power	60	20
Heating, lighting	30	15
Maintenance	220	20
Operator	650	650
Supervision	75	75
National Health	35	35
Employee services	40	40
TOTAL	£2,840	£1,360

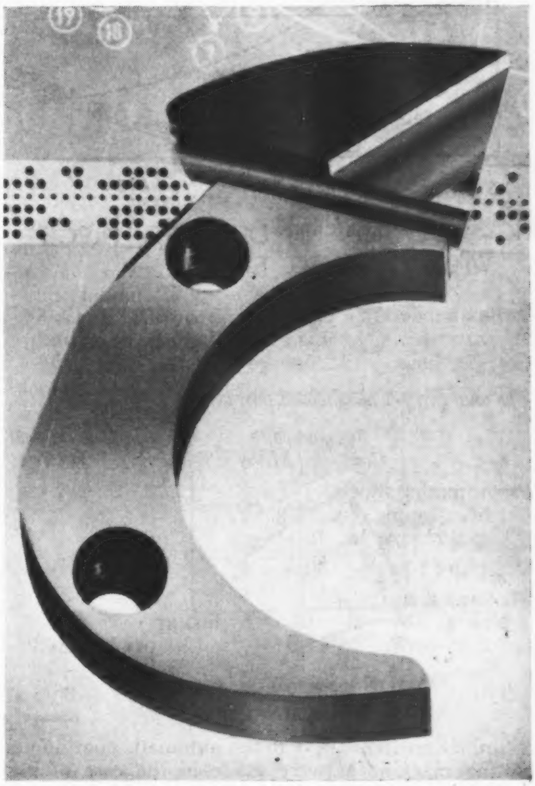

Fig. 2. Finger cam.

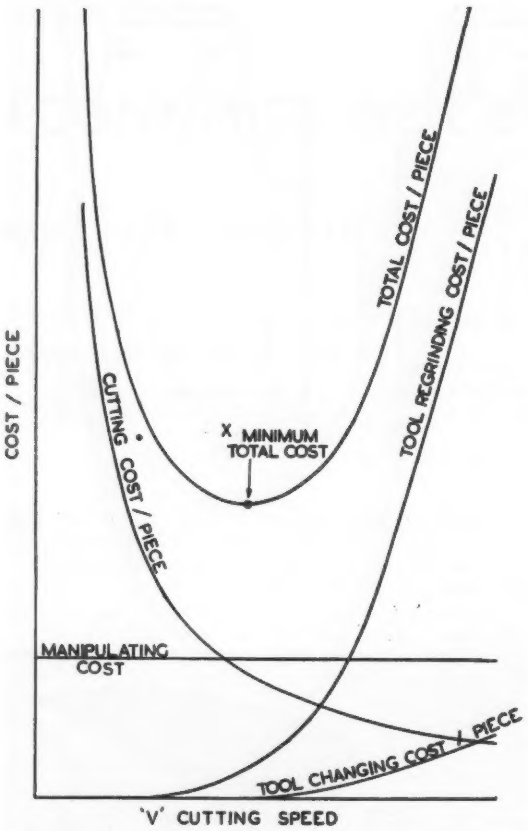

FIG. 3. RELATIONSHIP OF COST / PIECE WITH CUTTING SPEED 'V'

Utilisation at 80%	1,600 (hrs.)	at 90%	1,800 (hrs.)
Cost per hour	35/6		15/–

The total cost per piece would then be:

	Automatically Controlled Miller		Conventional Miller
Programming time: 1 hr. 20 mins. at 12/– per hr.	16/–		
Computer cost	30/–		
Machining cost: $\frac{1}{2}$ hr. at 35/6 per hr.	17/9	$5\frac{3}{4}$ hrs. at 15/– per hr.	86/3
TOTAL	63/9		86/3

Similar remarks apply to the automatic continuous cutting machine as were made in the case of the positioning machine.

It should be noted, however, that the machining times are much lower, therefore the rate of output will be greatly increased. Hence, greater attention will be necessary with respect to machine loading and production control to ensure maximum utilisation of these machines.

economics of the cutting process

overall economics

When examining the overall economics of a cutting process, cutting conditions have to be set to produce components at a minimum total cost.

The major factors comprising total cost are the cutting cost, the tool changing cost, the tool regrinding cost including depreciation per regrind, and manipulation cost.

Since tool life (hence tool cost) is a function of cutting speed, the problem is to select the cutting speed which will minimise the total cost per piece.

Fig. 3 illustrates the effect of increase of speed of cutting on each of the factors concerned, whilst the top curve shows the total cost with a minimum point at X. As shown in Appendix 1 the speed to give minimum cost is equated thus:

$$V \text{ (minimum cost)} = C \left(\frac{n}{1-n}\right)^{n} \left(\frac{1}{R}\right)^{n}$$

Where C = constant in Taylor's equation $VT^n = C$
n = exponent in above equation
R = Ratio

$$\frac{\text{cost of changing and regrinding tool} + \text{depreciation per re-grind}}{\text{cost of labour} + \text{overhead per min.}}$$

For example, if $C = 500$, $n = 0.25$, cost of changing tool = 6d., cost of regrinding tool = 30d., depreciation per regrind = 24d., cost of labour + overhead per min. = 6d., then:

$$V \text{ (minimum cost)} = 500 \left(\frac{0.25}{0.75}\right)^{.25} \left(\frac{6}{60}\right)^{.25}$$
$$= 500\,(.33)^{.25}\,(.1)^{.25}$$
$$= 500 \times .76 \times .56$$
$$= 212 \textit{ FPM}$$

Knowing the speed of cutting the total cost per piece can be computed. Such a computation is quite simple providing the values for all the factors are available.

The factors that will be known are cost of tool change, cost of tool regrind, depreciation per regrind, cost of labour and overhead per minute and the unknown factors will be those in Taylor's equation $VT^n = C$.

basic machinability data required

Because of the importance of Taylor's work some time will be spent in outlining its nature.

Fig. 4 shows a typical Speed/Life curve. In this instance the work material is S.99 and the tool material 18% tungsten, 5% cobalt.

If this curve is drawn on log/log paper as shown in Fig. 5, the slope of the line will give the value of 'n' and the intersection of the curve with the line for one minute tool life will give the value of 'C'.

Such a curve applies to one set of conditions only and should feed/rev. (chip thickness) or tool material or tool geometry be altered then different values will

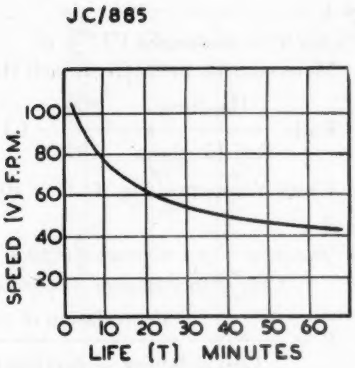

FIG. 4. SPEED/LIFE RELATIONSHIP NATURAL SCALES.

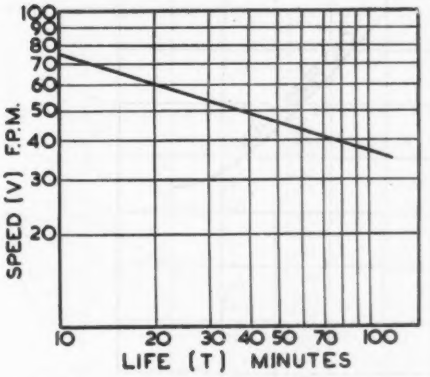

FIG. 5. SPEED/LIFE RELATIONSHIP LOG/LOG SCALES.

be obtained. If chip thickness is reduced the value of (C) will normally be increased and vice versa.

If tool material is altered the value of 'C' will be altered and also the value of 'n'. Hardness of material will also affect the value of 'C'.

However, to simplify the application of this data, values for 'C' for various materials are established with a standard 18–4–1 H.S.S. tool, cutting a chip of 0.010 in. thickness, as shown in Table I, and should a different tool material be employed then the values of 'C' and 'n' would be modified, using the correction factors shown in Table II.

TABLE I

Numerical values of 'C' for 18–4–1 H.S.S. tool.
Depth of cut = 0.10 in. Feed = 0.010 in. Soluble oil = 1 : 15.

Material	*Condition*	*Brinell Hardness*	'C'
SAE 1020	HR	127	350
SAE 1030	HR	168	270
SAE 1040	HR	187	210
SAE 1050	HR	201	170
SAE 1060	HR	217	145

TABLE II

Tool Material	*Multiplying Factor for 'C'*	'n'
H.S.S. 18–4–1	1.0	0.125
H.S.S. 5% Cobalt	1.1	0.135
Cast Alloy (Stellite)	1.3	0.150
Tungsten Carbide	3.5	0.250

Should the chip thickness be altered, then the value of 'C' would be corrected accordingly. For some investigations carried out at the College, the affect of chip thickness on the value of 'C' was given by the equation $C = \left(\dfrac{0.010 \text{ inches}}{\text{Chip thickness}}\right)^{0.6}$

Correction factors for chip thickness are shown in Table III.

TABLE III

Chip thickness	*Multiplying Factor for 'C'*
0.0025	2.30
0.0050	1.50
0.0100	1.00
0.0150	0.80
0.0200	0.67
0.0300	0.50

Before determining Speed/Life curves it is necessary to establish the optimum tool geometry for the material/tool combination as may be seen in Fig. 6, which is for S.99 material using 18% W, 5% C., H.S.S. tool. The most important angle in tool geometry is primary rake and it will be seen from the illustration below that the choice of primary rake has considerable influence on tool life.

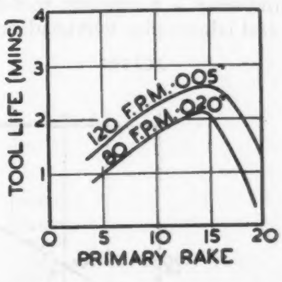

FIG. 6 TOOL LIFE / PRIMARY RAKE RELATIONSHIP

NOTE:- ALL GRAPHS REFER TO S99 MATERIAL AND 18 W. 5Co TOOL

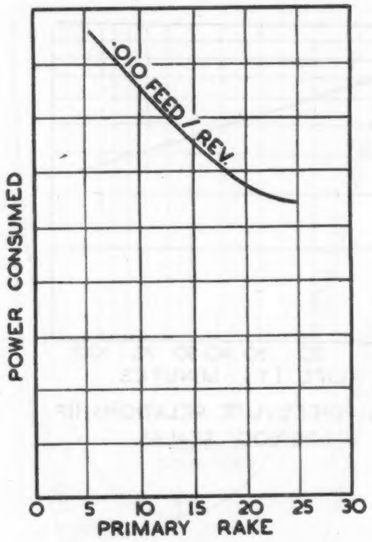

FIG. 7. POWER/PRIMARY RAKE RELATIONSHIP

It will also be seen, from Fig. 7, that primary rake has a considerable effect on power consumption and once optimum tool geometry has been established, the volume of metal removable per horsepower may be determined for estimating purposes.

Thus, having determined the optimum speed at a prescribed chip thickness, a comparison can be made of the power required with the power available and correction made if necessary.

application to turning

An application of the foregoing to a turning example is as follows:

Assume the optimum cutting speed has to be specified for turning a spindle 20 in. long of SAE 1040 HR material, 200 Brinell Hardness, at 0.005 in. feed/rev. using a T.C. tool, given: tool change time = 1 minute, tool regrind time = 6 minutes, tool depreciation cost = 30d., and labour plus overhead rate = 3d.

Step 1

To find 'C' in relationship $VT^n = C$

Material SAE 1040 HR, Brinell Hardness = 200

$$\text{Ratio } \frac{\text{Hardness}}{\text{Ref. Hardness}} = \frac{200}{187} = 1.1$$

Using Nomogram Fig. 8. $C = 1050$.

Step 2

To find speed 'V' for minimum cost/piece

$$R = \frac{\text{Cost of tool change} + \text{cost of tool grind} + \text{depreciation of tool}}{\text{Cost of labour} + \text{overhead per minute}}$$

$$= \frac{1 \times 3 + 6 \times 3 + 30}{3} = 17$$

Using Nomogram, Fig. 9 T (Life) = 48 mins.
V (Speed) = 400 FPM

Step 3

To find number of pieces per regrind

$$\text{R.P.M.} = \frac{400 \times 12}{11 \times 4} = 380$$

Traverse rate = 380 × 0.005 = 1.9 in./min.

$$\text{Cutting time} = \frac{20}{1.9} = 10.6 \text{ min.}$$

Tool life T = 48 mins.

$$\text{Number of pieces per regrind} = \frac{48}{10.6} = 4.5$$
say 4 pieces

application to milling

Whilst the application of the foregoing relationship to turning is relatively straightforward, the application to milling operations is much more complex; however, some experimental work conducted at the College of Aeronautics some time ago may give a lead to its use.

JC/886

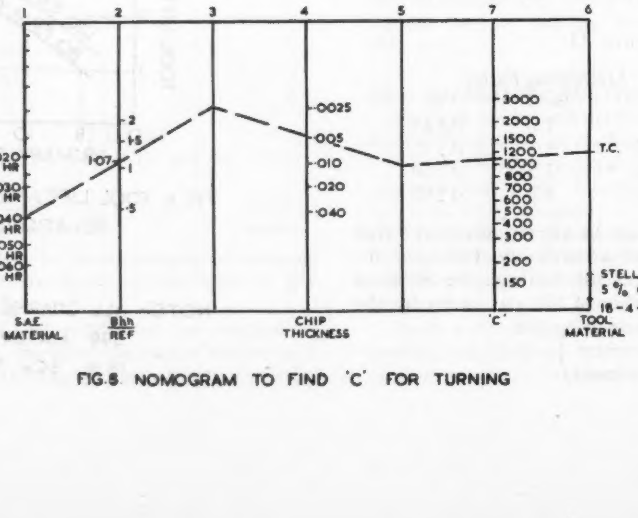

FIG. 8. NOMOGRAM TO FIND 'C' FOR TURNING

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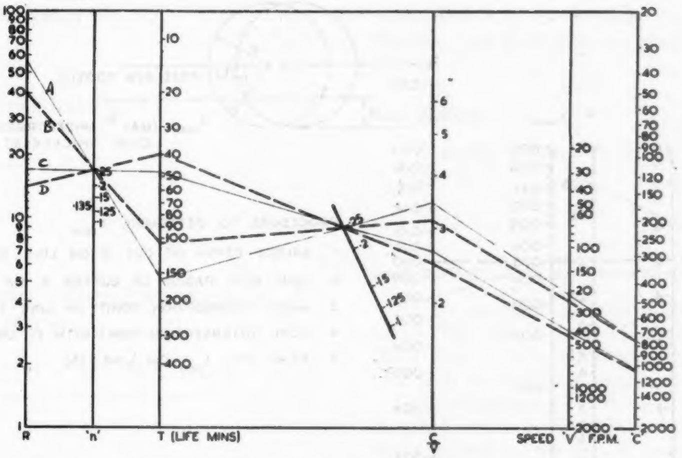

FIG.9. NOMOGRAM TO FIND SPEED (V) F.P.M.

In the course of investigations into milling S.99 material a correlation was found between the tool life for cylindrical milling and the tool life for turning, when maximum chip thickness for milling was compared with feed/rev. for turning, and when the sum of the times the milling cutter tooth was engaged in cutting (equivalent continuous cutting time) was compared with the continuous life of the turning tool.

More work is required to establish such a correlation for general application, but its basis is logical although a factor may have to be applied to suit specific conditions.

Accepting this as a working basis, then the application to milling would be as follows.

cylindrical milling

As an example in the application of this correlation, assume a bar of SAE 1040 HR material, 200 Brinell Hardness, 20 ins. long has to be cylindrically milled using a $2\frac{1}{2}$ in. diameter T.C. cutter with four teeth, taking $\frac{1}{4}$ in. depth of cut, with 0.005 in. maximum chip chickness.

Cutter change cost $= 5$ mins. $\times 3 = 15$ pence; cutter regrind cost $= 30$ mins. $\times 3 = 90$ pence; cutter depreciation cost $= 60$ pence; labour plus overhead per minute $= 3$ pence.

To find 'C'—The value of 'C' would be obtained from Nomogram Fig. 10.

'C' $= 750$

To find 'V'

$R = 165/3 = 55$

From Nomogram Fig. 7

$T = 160 \quad V = 210$

To find number of pieces per regrind:- From Nomogram Fig. 11.

Feed/Tooth $= 0.008$

$$\text{Traverse rate} = \frac{210 \times 12}{\pi \times 2.5} \times 4 \times 0.008$$

$$= 10.2 \text{ in./min.}$$

$$\text{Time/piece} = \frac{20 + 1 \text{ (approach)}}{10.2} = 2.05 \text{ mins.}$$

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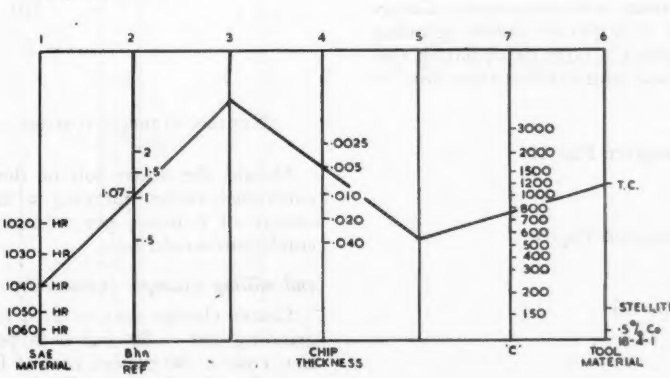

FIG.10. NOMOGRAM TO FIND 'C' FOR MILLING

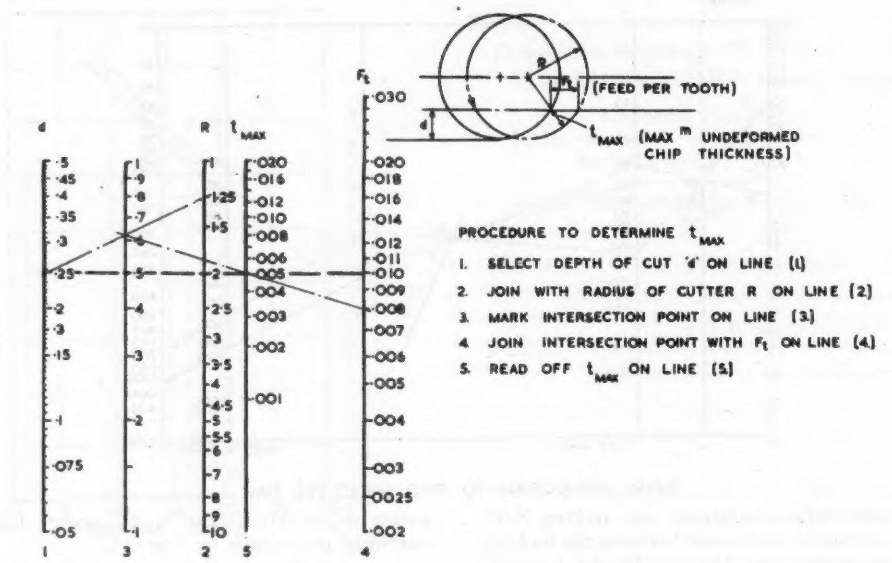

FIG.11. TO DETERMINE t_{MAX} (MAXIMUM UNDEFORMED CHIP THICKNESS.)

Total cutting life of cutter = 24 hours (from Nomogram Fig. 12)

Number of pieces per regrind = 700.

end milling

The extension of the relationship to end milling is obvious, although greater complexity will arise with cutter deflection and machine/cutter limitations would require to be established in a given case.

When the task is within the capability of the machine, then the application would be as follows.

end milling example (*conventional miller*)

Assume a bar of SAE 1040 HR Brinell Hardness 200 is to have a slot 1 in. diameter × 20 in. long end milled using a T.C. cutter with four teeth. Cutter change cost = 2 × 3 = 6 pence; cutter grinding cost = 30 × 3 = 90 pence; cutter depreciation cost = 60 pence; cost of labour plus overhead per min. = 3 pence.

To find 'C'—From Nomogram Fig. 10.

'*C*' = 750

To find 'V'—From Nomogram Fig. 9.

$$R = \frac{6 + 90 + 60}{3} = 49$$

$T = 150$
$V = 220$

To find number of pieces per regrind:- From Nomogram Fig. 11.

Feed/Tooth = 0.005

$$\text{Traverse rate} = \frac{220 \times 12}{\pi} \times 4 \times 0.005$$

$$= 16.8 \text{ in./min.}$$

$$\text{Cutting time/piece} = \frac{20}{16.8} = 1.2 \text{ min.}$$

$$\text{Total cutting time} = \frac{5 \text{ hrs. } 10 \text{ mins.}}{2}$$

$$= \frac{310}{2} = 155 \text{ mins. (Nomogram Fig. 12)}$$

$$\text{Number of pieces/regrind} = \frac{155}{1.2} = 130$$

Should the above job be done on a numerically controlled miller carrying a labour plus overhead charge of 6 pence per minute, then the optimum conditions would be.

end milling example (*numerically controlled miller*)

Cutter change cost = 2 × 6 = 12 pence; cutter grinding cost = 30 × 3 = 90 pence; cutter depreciation cost = 60 pence; cost of labour plus overhead per minute = 6 pence; all other conditions as for conventional miller.

To find 'C'—From Nomogram Fig. 10.

$'C' = 750$

To find 'V'—From Nomogram Fig. 9.

$$R = \frac{12 + 90 + 60}{6} = 27$$

$T = 75$ mins.
$V = 280$ FPM

To find number pieces/regrind—From Nomogram Fig. 11.
Feed/Tooth = 0.005 in.

$$\text{Traverse rate} = \frac{280 \times 12 \times 4 \times 0.005}{\pi}$$

$$= 21.5 \text{ in./min.}$$

$$\text{Cutting time/piece} = \frac{20}{21.5} = 0.93 \text{ mins.}$$

Total cutting time = 75 (Nomogram Fig. 12)

$$\text{Number of pieces/regrind} = \frac{75}{0.93} = 81$$

It will be observed that a faster rate of production is more economical in the case of the numerically controlled machine because of the higher overhead charge. This principle, of course, has a general application.

face milling

A similar approach can be made to face milling as follows.

face milling example (*conventional miller*)

As an example of face milling, assume a bar of SAE 1040 HR, Brinell Hardness 200, 3 in. wide × 20 in. long to be face milled with a 4 in. diameter T.C. face mill having four teeth.

Cost of changing cutter = 4 × 3 = 12 pence; cost of grinding cutter = 45 × 3 = 135 pence; cost of depreciation = 60 pence; cost of labour plus overhead per minute = 3 pence.

To find 'C'—From Nomogram Fig. 10.

$'C' = 750$

To find 'V'—From Nomogram Fig. 9.

$$R = \frac{207}{3} = 69$$

$T = 180$ mins.
$V = 200$ FPM.

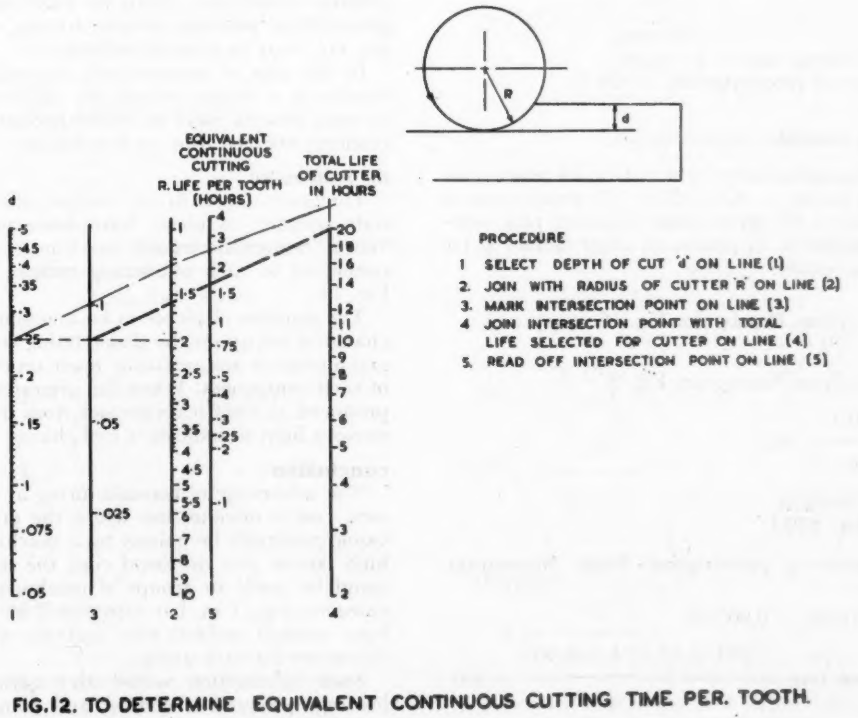

FIG. 12. TO DETERMINE EQUIVALENT CONTINUOUS CUTTING TIME PER. TOOTH.

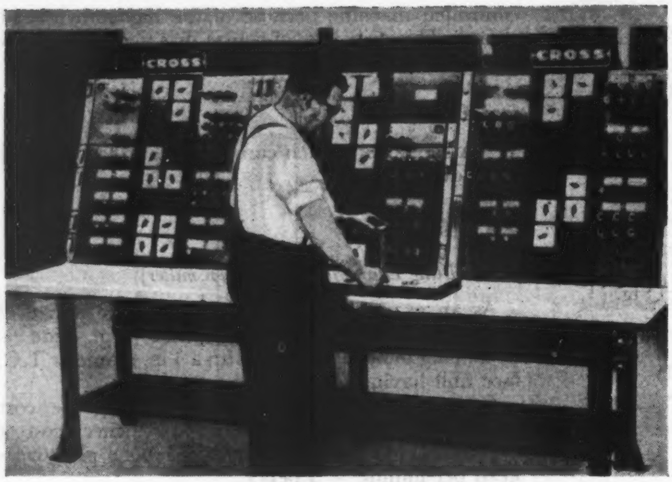

Fig. 13. Machine tool control unit with toolometers.

To find number of pieces/regrind:- From Nomogram Fig. 11.

Feed/Tooth = 0.005 in.

$$\text{Traverse rate} = \frac{200 \times 12 \times 4 \times 0.005}{\pi \times 4}$$

$$= 3.8 \text{ in./min.}$$

$$\text{Cutting time/piece} = \frac{20 + 0.75}{3.8} \text{ (approach)}$$

$$= 5.45 \text{ mins.}$$

Total cutting time = 14 hours
Number of pieces/regrind = 154

face milling example *(numerical miller)*

Cost of changing cutter = 4 × 6 = 24 pence; cost of grinding cutter = 45 × 3 = 135 pence; cost of depreciation = 60 pence; cost of labour plus overhead per minute = 6 pence; all other factors as for conventional miller.

To find 'C'—From Nomogram Fig. 10.
'C' = 750

To find 'V'—From Nomogram Fig. 9.

$$R = \frac{219}{6} = 36.5$$

T = 100 mins.
V = 240 FPM.

To find number of pieces/regrind:- From Nomogram Fig. 11.

Feed/Tooth = 0.005 in.

$$\text{Traverse rate} = \frac{240 \times 12 \times 4 \times 0.005}{\pi \times 4} = 4.6$$

$$\text{Cutting time/piece} = \frac{20 + 0.75 \text{ (approach)}}{4.6}$$

$$= 4.5 \text{ mins.}$$

Total cutting time = 7 hours

$$\text{Number of pieces/regrind} = \frac{420}{4.5} = 93$$

It will be seen for each process illustrated that different conditions obtain for each minimum cost/piece. Other processes such as drilling, boring, reaming, etc., may be treated similarly.

In the case of automatically controlled machines employing a variety of tools the optimum conditions for each process could be established and the greatest economy effected from such machines.

the toolometer

To ensure that tools are changed after the appropriate number of pieces have been machined, the "Cross" automatic transfer machine has a toolometer connected to each machining station, as shown on Fig. 13.

The number of pieces to be machined before tool change is set up on the dial relating to each process and a count is automatically made on the completion of each component. When the prescribed quantity is produced an electrical interlock stops the process and shows a light to indicate a tool change is required.

conclusion

The advantage of manufacturing at the minimum total cost is obvious and whilst the greatest benefits would naturally be gained by a machine carrying a high labour plus overhead cost, the same approach could be made to groups of machines in the same category, e.g., 1 in. bar capstans, 2 in. bar capstans, light vertical millers, etc., and the optimum conditions set for each group.

Such information would also assist in machine loading, production control and standard costing,

but unfortunately, whilst the basic approach is known, insufficient experimental data is available for widespread application to British materials and most of the foregoing information has been culled from American sources, in particular the A.S.M.E. Manual on Cutting Metals.

It is felt, however, that much could be achieved in a year or two if a concentrated effort were made by research establishments and industry to provide basic machinability data for setting optimum standards of performance.

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APPENDIX I

optimum machining conditions

Total Cost = Manipulation cost and cutting cost + tool changing cost and tool grinding cost.

Let A_1 = Direct labour rate + O/H rate (pence/min.).

A_2 = Tool cost per grind including depn (pence).

L = Length of part (ins.).

D = Dia. of part (ins.).

V = Cutting speed (ft./min.).

F = Feed rev. (ins.).

$T.C.T.$ = Tool changing time (mins.).

$V T^n$ = C. Cutting speed/tool life equation.

T = Tool life (mins.).

Manipulation cost/piece

= A_1 × total manip. loading, plus idle time per piece.

Cutting cost/piece

= A_1 × cutting time/piece

$$= A_1 \times \frac{L\ \pi D}{12 V f}$$

Tool changing cost/piece

= A_1 × tool failures per piece × tool changing time

$$= A_1 \times \frac{\text{Time for 1 piece}}{\text{Time to tool failure}} \times T.C.T.$$

$$= A_1 \times \frac{L \pi D}{12\, V f} \times \frac{1}{T} \times T.C.T.$$

$$= A_1 \times \frac{L \pi D}{12\, V f} \times \frac{V^{1/n}}{C^{1/n}} \times T.C.T.$$

$$= A_1 \times \frac{L \pi D}{12\ f} \times \frac{V^{1/n}}{C^{1/n}} - 1 \times T.C.T.$$

Tool regrinding cost/piece

A_2 × tool failures/piece

$$= A_2 \times \frac{\pi D L V^{1/n}}{12 f C^{1/n}} - 1$$

Therefore Total Cost per piece

= A_1 × manipulation time +

$$A_1 \times \frac{\pi D L V}{12 f} - 1 + \frac{K_1 \pi D L V^{1/n}}{12 f C^{1/n}} - 1\ T.C.T.$$

$$+ A_2 \frac{\pi D L V^{1/n} - 1}{12 f C^{1/n}}$$

For minimum cost the above expression is differentiated with respect to Speed (V) to equal zero.

$$\text{therefore } \frac{\text{d/cost/piece}}{dV} = O$$

$$O = O A_1 \frac{\pi D L V^{-2}}{12 f} + (1/n - 1)$$

$$A_1 \frac{\pi D L V^{1/n - 2}}{12 f C^{1/n}}\ T.C.T.$$

$$+ (1/n - 1) A_2 \frac{\pi D L V^{1/n}}{12 f C^{1/n}} - 2$$

$$A_1 V^{-2} = (1/n - 1) \frac{V^{1/n} - 2}{C^{1/n}} (A_1\ T.C.T. + A_2)$$

$$A_1 = (1/n - 1) \frac{V^{1/n}}{C^{1/n}} (A_1\ T.C.T. + A_2)$$

$$V^{1/n} = \frac{A_1 C^{1/n}}{(1/n - 1)} (A_1\ T.C.T. + A_2)$$

$$V^{1/n} = \frac{C^{1/n}}{(1/n - 1) \left(\frac{A_1\ T.C.T. + A_2}{A_1} \right)}$$

therefore

$$V = \frac{C}{(1/n - 1) \left(\frac{A_1\ T.C.T. + A_2}{A_1} \right)^n}$$

Tool life for minimum cost

Since $VT^n = C$

$$V = \frac{C}{T^n}$$

$$T\text{ min.} = (1/n - 1)\left(A_1 \frac{T.C.T.}{A_1} + A_2\right)$$

$$= (1/n - 1)$$

$$\left(\frac{\text{Cost of changing and regrind tool plus depreciation}}{\text{Cost of labour} + \text{O/H/Min.}}\right)$$

$$= (1/n - 1)\ R_1$$

Cutting speed for minimum cost

$$V\text{ min.} = \left(\frac{C}{T\text{ min.}}\right)^n$$

$$= C\left(\frac{n}{1-n}\right)^n\left(\frac{A_1}{A_1 T.C.T.}\right)^n$$

$$= C\left(\frac{n}{1-n}\right)^n$$

$$\left(\frac{\text{Cost of labour and O/H/Min.}}{\text{Cost of changing and regrind tool plus depreciation}}\right)^n$$

$$= C\left(\frac{n}{1-n}\right)^n\left(\frac{1}{R}\right)^n$$

DISCUSSION

Chairman: Dr. G. S. Brosan, M.I.Prod.E.

Mr. F. W. Cooper (*Institution Education Officer*), opening the discussion, said that what he had been interested in, as an amateur in these matters, was the important inter-relation between the economic factors of deciding cutting speeds and so on, on a numerical machine. It might be obvious, and perhaps one should have thought of it long ago, but it seemed an important application for such types of machine tools.

There were, in advanced technical colleges, adequate facilities nowadays, but a dreadful shortage of the type of man needed to undertake this research work. One might mention such places as Birmingham and Loughborough, and it was a miserable story generally. It would be very nice if the people trying to co-ordinate the research could include the advanced technical colleges in the scheme.

The mathematics in the Paper were not formidable, but went a little beyond what was required by the traditional qualifications of the pre-1960 production engineer, which year the scheme had been changed. It did emphasise the necessity for the young production engineer to have a higher standard of mathematics than hitherto. He hoped that the facilities in the advanced technical colleges would be used, because the fact that they had not such figures themselves was really a dreadful indictment.

Mr. Cherry said that they would like to bring technical colleges into the plan. With a co-ordinated programme useful information could be gained in a very short time. It was a matter of getting people interested, and one or two research people working on it full-time. The views of the Symposium members would be of interest.

Mr. I. S. Morton (*Senior Technical Adviser, Shell International Petroleum Co.*) said that the A.S.M.E. Manual, apart from dealing with American materials, seemed to rely mainly on prewar information for its basic data. It was based on high speed steel tools, with conversions to estimate tool life with carbides.

He agreed that research students could produce a good deal of valuable information in a year or two, but wondered whether this time would be enough. Taylor had, because of his immensely valuable work, been taken by Mr. Cherry as the starting point. When he had begun his management studies in the 80's, he had realised that he needed to know a little about machining to get his times right. His estimate had been six months, but 25 years had passed before he produced his classic Paper (in 1907) to the A.S.M.E. Another 30 years followed before the A.S.M.E. compiled the data now being discussed. When, 20 years ago, The Institution of Production Engineers had had a Research Department, the compilation of such data was considered an important feature of its programme, but it had never been done because of other commitments. Then PERA was to have done it, but had been doing other important things — and so it went on.

He would like to see the whole weight of the Institution thrown behind the present effort. In reply to the suggestion that people had managed without

this data, he would say that this had been because of the " know-how " in the shop, and the (unpublished) information tied up in process and rate departments. A vast amount of material was published every week in journals such as *Machinery* and *Metalworking Production*. The trouble was that it was from diverse sources and often not sufficiently detailed. Nevertheless, a single rational compilation of practical use might be made from such sources. The task would be like making a new windscreen from the shattered fragments of the old, but someone with sufficient perception might be able to do it. He would not accept the view that it was a pedestrian undertaking and something less than research — it was information which was badly needed. Perhaps Cranfield, with its distinctly practical approach, might also consider doing something on those lines.

Mr. Cherry replied that the full weight of all concerned should be put behind the effort, because it would certainly pay off, and the sooner the better. What was already known would be the starting point. One would try to confirm other people's experience, accept data already published, where it applied to British materials, and fill in the gaps. Enough information to be helpful could be gathered in a year or two. One might not be able to cover all the processing, but could certainly tie up, say, turning. It depended on the weight put into it. With collaboration on the part of other research centres, the time would be shortened.

The A.S.M.E. handbook was useful, but one would like to work with more up-to-date tool materials. Some tests had been done on tungsten carbide, but nowadays there was a whole range of these. More work should be done on the different grades.

Mr. K. J. Hume (*Reader in Engineering Production, Loughborough College of Technology*) supported the suggestion for collaboration in cutting tool research between Cranfield and other colleges, particularly those with developing facilities. In the expression for tool life, Mr. Cherry, in going from turning to milling, had made certain assumptions. Had he done any experiments to see if one could actually transfer this from the continuous turning action to the intermittent milling action? There was what one might call an impact factor, especially with tungsten carbide, which one always assumed was rather sensitive to intermittent cutting.

Mr. Cherry said that a correlation had been discovered during their tests on the milling of B.S. S99 material, the results of which were referred to in the Bibliography. Establishing correlation could be difficult because, in going from turning to milling, the tools might be changed. Much attention had to be paid to keeping the factors constant. Experience had shown that differences in tool material would give results that would never agree.

Describing the experiment, Mr. Cherry said that the milling results had been plotted against the turning results for various chip thicknesses. A lot more work had to be done, but this seemed to be the logical approach.

Mr. L. J. Blache asked whether any firms in England had made use of the procedure described in the Paper and how the results had compared economically. Mr. Cherry had said that tool life was determined by wear, and change of tool geometry. Had this been selected as the best indication of tool wear? How did it compare with, say, the change in surface finish or the increase of tool deflection against the workpiece, thereby affecting the position of cutting?

Mr. Cherry did not know of any firm that used the procedure, but said that the College liked to point the way. Many companies did experiments to try, empirically, to ascertain optimum conditions.

He had been referring mainly to rough cutting processes in which case the wear land would not be the criterion, but if one were talking about finishing, it might be that the surface finish itself would be the criterion, so one would have to set up the conditions to suit the job. It might be suitable for one material up to say, 40 ton steel, to accept a wear land of 0.030 in. but when one came to the machining of titanium one's tool would break down around 0.010 in. Therefore the criterion must be chosen in relation to the workpiece material and the work one was doing. There was no single criterion.

In the case of turning with a high speed steel tool at low cutting speeds, as for milling, the criterion might be not wear land at all, but cratering. It might be the depth of crater that one was prepared to re-grind. In this case the cutting forces decreased as the crater increased.

Mr. W. Walker (*Metal Cutting Research Engineer, A.E.I. (Manchester) Ltd.*) felt that this sort of information should be percolating through to the engineers who were actively engaged in fixing cutting conditions. The principle had been put forward in A.E.I. (Manchester) Ltd. for about 10 years. For the last three or four years it had been intensively pushed by lectures to machine tool and cutting tool engineers.

However, there were some pitfalls. Having chosen the most economic cutting speed, one might produce a piece that was not acceptable by the inspector. It might fail on surface texture. This was not wholly overcome by changing the tool profile. One might have to change the cutting speed and other factors that had not been mentioned in Mr. Cherry's analysis. Some of the information was based on the hardness of the material, and the relation between hardness and machinability was a very vague one. Some materials were quite soft and difficult to machine.

In the milling analysis, Mr. Cherry had taken a theoretical maximum chip thickness into his analysis. One could tell by walking past the machine when this figure was no longer applicable : one could hear evidence that only one or two teeth were removing most of the metal. The analysis made was a good basis, but by no means the whole story. Sometimes, also, the size of the batch was much less than the optimum

number of pieces for re-grind. Under those conditions the optimum speed was the fastest cutting speed that would enable the batch to be completed. In the case of milling, the feed rate was the most important parameter : the most economical condition was the highest feed rate that would complete the batch with the tool ready for a re-grind.

The Paper had contained a curve (Fig. 6), showing tool life versus primary rake for the angle selection of the optimum tool geometry. The curve was asymmetric, having a maximum at 15°, this value being the optimum primary rake. An increase of about 1° could have resulted in a great diminution of tool life. If the author had chosen a value, not of 15° primary rake, but about 12° or 13°, he would have been on much safer ground, in that he would have allowed for errors in grinding.

Mr. Cherry said that these were useful comments. The ultimate criterion was satisfactoriness of the workpiece. Surface finish might be a function of rate of feed. It might be that one could not take anything like 0.005 in. feed/rev. but rather 0.001 in. in order to get the surface finish wanted with the tool geometry suitable. He agreed that these were pointers, which might have to be modified in particular cases, but did not feel that that detracted from their value. They were not ready-made answers, but rather signposts that would take one somewhere near the ultimate, small adjustments having to be made in practice.

Hardness could be misleading : it was machinability that counted. With the normal run of steels, hardness and machinability were reasonably related. but this was not the case in work-hardening steels. Once chip thickness was less than 0.005 in., one was not getting under the work-hardened layer and tool life would diminish. These were special cases, which had to be investigated. Run-out on milling machines was another factor.

In regard to tool life and primary rake, he would agree that in practice one would err a little on the safe side, particularly in the milling operation, because shock loading was coming in as well, and one would prefer having a stronger tooth rather than a weaker. One might say, "The ideal looks as if it would be 15°, but with shock loading coming in we may go back to 1° or 2°." It had to be modified in the light of experience.

Mr. A. Dobson (*Methods Engineer, R.O.F.*), referring to the economics of cutting tools, said that more emphasis should perhaps have been laid on the fact that the formulae used were drawn up by Taylor some 80 years ago; that they were entirely empirical and based on observations made in a fairly primitive machine shop of which, incidentally, Taylor had been foreman. In the absence of considerably more research, they could not be used safely in conditions which were so very different.

In Taylor's time tool grinding costs had been a relatively simple factor. The tools used had been carbon steel and grinding had mostly been done by the operator; but in a modern machine shop a grinding compound was provided which had to be kept available irrespective of the number of tools ground. Therefore the cost of grinding a tool was not a simple constant, but varied in inverse proportion to the number of tools ground.

Another factor to be considered in determining optimum cutting speed was that one could regrind up to the economical saturation point of the grinding compound.

Mr. Dobson's own organisation had approached the question in a different way. They used expendable carbide tool tips, each point being used consecutively until the whole of the tip was exhausted. It was then thrown away. At about 10s. a tip, this was worthwhile, and the re-grinding service could be completely dispensed with.

Mr. Cherry said that the formula showed that the speaker's point about disposal of tips was sound. If one had no grinding costs and tool change cost was low, one could see the advantage right away of throw-away tips, compared with standard tools. They did not simply accept Taylor's work, and did actual tests of their own ,but his work was still valid for practical purposes. The main benefit to be derived from the formula was the way in which it threw up the cost of grinding and tool change.

Mr. J. W. East (*Assistant Manager, War Office, R.O.F.*) said that Mr. Taylor's work had been suggested as a starting point for research, from the point of view of confirming it with new materials. He felt that the problems studied should be more up-to-date. They had seen laboratory experiments on cross-chord cutting, which presumably would become very popular, especially with the harder materials. There were also the newer factors affecting tool geometry where one used to a great extent positive and negative rakes, negative primary and positive secondary rakes and, in fact, some tool cutting edges which were rounded. If research were to be real, it should be directed to the newer techniques of tool geometry rather than attempt to confirm that evaluated by Taylor so long ago.

Mr. Cherry replied that in any investigation made they would certainly look at the tool geometry in the light of up-to-date knowledge. He had meant to imply that a good deal of the information available on American materials could probably be translated to British materials relatively quickly, and be used while the other work was proceeding.

Mr. W. Hird (*Senior Lecturer in Production Engineering, Twickenham Technical College*) referring to the opening of the Paper, felt that Mr. Cherry had shown some bias in favour of the hour-cost of the controlled borer. He could see no reference to repayment for capital, or interest on capital. Surely £13,000 difference in capital cost would seriously put up the cost per hour of the automatically controlled borer, unless allowances for it had been made in "Depreciation per annum"?

Further on in the Paper under "Step 3", the

cutting time had been given as $\frac{20}{1.9} = 1.06$ min. The fact that the component was 20 in. long had not been mentioned and one did not realise this until one came to the next problem.

In the end milling example (conventional miller) several references had been made to the Taylor formula $VT^n = C$, but no mention had been made of the depth of slot. Mr. Hird suggested that this formula could be true only for a specific set of cutting conditions. If one increased the depth of cut, then one had to alter the cutting speed, otherwise the load on the cutter would increase and the tool life would be reduced.

Mr. Hume had referred to relative cutting speeds for turning and milling. Mr. Hird wished to support and amplify this. There was a school of thought — actually substantiated in one or two textbooks — that if one used exactly similar conditions when one was turning and milling, one could mill at a faster cutting rate than one could when turning. The argument was that because one was turning at a constant cut one generated a good deal of heat energy: whilst in milling, the cutter tooth was cutting for only a short period during each revolution — he was referring to roll milling — and did not generate heat, thus making it possible to run the cutter faster. He did not agree, because if the argument was right it would follow that if one turned a piece of 2 in. diameter material at a certain optimum cutting speed and then a piece of square material, 2 in. across the diagonal, one could turn the square piece faster than the round. One knew, from the practical point of view, that this was nonsense.

On the question of whether one could relate a 0.005 in. feed on turning to a 0.005 in. undeformed chip thickness on milling, he would suggest that the author's finding was wrong. He assumed from the diagram that up-cutting milling was being used. If so, the tooth began at minimum thickness. As was well-known, a good deal of wear took place at that particular point and the cutter would wear more quickly than if down-cut milling was being used. Had the author any comments on this?

To return to Mr. Cooper's remark about the mathematics involved, for many years now Mr. Hird had been setting papers at Ordinary and National Certificate and Diploma level. Some 10 years ago he had set a paper at O.N.C. level on workshop technology. In the main, S3 students were not production engineers. Their first contact with the teaching of it was in workshop technology. The cutting tool section of the syllabus could not allow for more than about three weeks of tuition.

The question had been: "Explain and give examples of cutting speeds and cutting feeds as used in machine shop practice." In the main it had been done quite satisfactorily. A second part of the question was a numerical example. He would mention that these candidates were men who were already studying the calculus. In all cases they were, of course, mechanical engineers, but not necessarily production engineers. The question was: "A twist drill 1 in. diameter is running at a cutting speed of 60 ft./min. and feed rate of 0.005 in./rev. Calculate the time required to drill through a piece of 1 in. mild steel." Sixty out of a 100 students had given the answer in half a line—"Cutting speed 60 ft./min., there, 1 ft./sec; material 1 in. thick — drilling time 1/12 sec." They had had only to look at it to realise that it was nonsense. He would suggest to Mr. Cooper and the members of the Institution's Education Committee that serious consideration should be given to the introduction of more and more actual production engineering subjects not only at H.N.C. level but, if possible, O.N.C. level, where students had little workshop experience.

Mr. Cherry said that the interest on capital would be included; it was necessary to work within the firm's accountancy system. The main point that he wanted to bring out was on comparative costs of automatic control and conventional machines, since in any given circumstances one could probably prove that the automatic machine would be more economical. However, it must be kept fully employed. It must be working for 12 months of the year and at 80% utilisation, or the costs would be very much higher.

One must be able to calculate or establish the limitations of cutter depth with a particular material for that particular machine. Tests to establish this could be made. He would not agree entirely that the depth of cut would affect the life of the tool.

Reverting to the question of turning, if the radius were small in relation to the depth of cut, the life of the tool would be the same whether one took a $\frac{1}{2}$ in. cut or a $\frac{1}{4}$ in. cut, because the cutting force was being distributed over a greater area. There were tables in the A.S.M.E. manual — and they had found it at the College also — to show that the depth of cut did not affect life, provided the radius were not influencing it. If the radius was large, one was not getting the theoretical chip thickness. It did affect power and deflection. He had passed over that quickly because it represented another step that had to be taken in respect of each application.

Mr. Hird was right in being dubious about the application of turning data to milling. In their investigation, which was analogous to cylindrical milling for machining S99, and for turning, their correlation had been obtained when they had taken maximum chip thickness.

In regard to up-cut milling producing erosion, if they had taken 0.003 in. instead of 0.005 in. their values would have been higher but, possibly because of the abrasion, it was the maximum chip thickness that was related to feed/rev. With down-cutting it might have been different. More work had to be done in this aspect. It had obtained in this particular set of circumstances. In the Paper he had said: "In the course of investigations into milling S99 material a correlation was found between the tool life for cylindrical milling and the tool life for turning, when maximum chip thickness for milling was compared

with feed/rev. for turning, and when the sum of the times the milling cutter tooth was engaged in cutting (equivalent continuous cutting time) was compared with the continuous life of the turning tool. More work is required to establish such a correlation for general application."

Mr. J. Sargrove (*Automation Consultants & Associates Ltd.*) congratulated the author on having undertaken such meaningful research, and written it up in such detail. It was important for Britain that it did not lag behind, and the appeal for more research should be supported.

With numerically controlled machines, which were themselves expensive, it seemed a good proposition to use the most expensive tool, with the longest life. Had any experiments been made with diamond tip tools? Such tips were used for cutting rock and drilling deep holes in the earth's crust because of the expense of the whole operation, which made it worthwhile. There seemed to be a surfeit of diamonds in the world, the majority being used for adornment. Their use in this new field might trigger off the greater use of diamonds for real operations! It tied in with the suggestion that a tool should be used until it was of no further value for that purpose. Throw-away diamond tips could perhaps be disposed of to people who made diamond bonded wheels and the like.

On the question of tool life, could the College make experimental tools in which the tungsten carbide insert, when brazed in, was also fitted with a high temperature strain gauge which was then, perhaps, brought out through the back and to include also a built-in thermocouple?

Mr. Cherry replied that diamond tools were, of course, the hardest, but with hardness came brittleness. Diamond tools could be put in a grinding wheel but were not very satisfactory, particularly for milling, because of impact loading. They were used to a great extent in the machining of soft materials such as brass, aluminium and aluminium alloys, but where shock load was present they were liable to fracture. With good tool holding and design their use might be possible.

A thermocouple was used in the College for measuring temperature. It gave an indication of when a tool was wearing. They had not used it on a practical basis.

Describing an experiment carried out in conjunction with a private firm, Mr. Cherry said that it had not proved a good practical application of the principle and more work would be done on it when time permitted.

Mr. R. H. Norris (*Staff Engineer, Mobil Oil Co. Ltd.*) said that in their own laboratory they used radio-active tracers as a means of determining tool wear. He thought that use of this modern technique would have been made at the College to secure a quick assessment of tool wear, and perhaps also speedily to find values for " n " and " C ". Was the use of radio-active materials in the near future being considered?

Mr. Cherry said that perhaps they should be used. His own approach was to go by the most direct route in finding out an answer. As he had mentioned, the criterion for tool wear was dependent on the workpiece material with which one was working, and on the type of process. With a Nimonic material, for example, one could stand only 0.010 in. wear land, and on a part with a good surface finish one might have a fairly large radius. Tool wear took place in at least two areas. If he were to measure the wear radioactively he would get a total figure; but what he wanted was separate figures for each.

Mr. Norris said that it might be possible to blank one section off from another, and make a check on flank wear as compared with crater wear.

Mr. Cherry said that these were his first reactions. As described, he was measuring the criterion affecting the workpiece, and not having other things thrown in to confuse the issue. However, it should perhaps be investigated.

Mr. C. F. Steventon (*Development Engineer, British Oxygen Gases Ltd.*) referring to the operating costs given for automatically controlled and conventional millers sympathised with Mr. Cherry because of the different approaches possible and the various factors that could be taken into consideration.

An alternative approach was that if one were faced with the need to produce at a certain rate of components per week, one would need something like 11 conventional millers, or one automatically controlled machine, to achieve it. This would result in a capital expenditure of £55,000 as against £17,000 for the automatically controlled miller. Interest on capital had already been mentioned, so this would be a point in favour of the latter machine.

Mr. Cherry said that every situation had to be assessed individually.

Mr. J. P. Mills (*Machine Tool Designer, H. Hobson Ltd.*) said that in other branches of research, e.g., mechanical and electrical engineering, certain standard testing machines had been established. He was thinking at the moment of gear research, in respect of which there were four such machines — at Pametrada Research Station, Newcastle, David Brown's and elsewhere. Could not standard machines for tool testing be designed for use at works and institutions in different parts of the country, so that results could be compared? This would eliminate one variable that everyone knew was important — the condition of the machine, the rigidity, resonant vibration frequencies and so on.

Mr. Cherry felt that this would be an ideal situation, though he personally would not like to be delayed in carrying out work while awaiting for that

to happen. One must start with good equipment. Probably the best way would be to have machines of the same design. He thought that one might then get along quite well while waiting for the ideal.

Mr. J. H. Shankland (*Lecturer in Engineering Production, University of Glasgow*) believed that the author was right in omitting reference to interest on capital in this case. "' Depreciation " clearly allowed for depreciation over 10 years and not interest, but interest payments would in any event be approximately cancelled out by the taxation relief allowance involved, assuming of course that the company earns profits and pays tax. It had no appreciable effect so far as the calculation was concerned.

Professor Loxham said that, so far as research was concerned, conversations had taken place between the College and other technical colleges, one or two universities, and the Ministry of Education. The College would very much like to take a fairly prominent part in it. Suggestions had been made that a small sub-committee, with representatives of various technical colleges and universities, and one or two industrialists, be appointed to investigate the problem; also that a biennial bulletin might be published. Manchester School of Technology brought out one on mechanical engineering education and another on electrical engineering education. Nothing appeared on the subject of production engineering education: it was much needed.

In the new machine tool laboratory at Cranfield they proposed to do not only cutting tests of the kind that Mr. Cherry had mentioned, but to carry out quite large-scale manufacture — not because they wanted to make a large number of pieces, but because they wanted to investigate the production problem. The aim was to make, not 10 pieces in front of a group of students, but a 1,000 pieces of the kind that would be needed on an industrial basis.

It was also hoped, in October, 1961, that it would be possible to begin some 10-week courses at which they would be able to propound the kind of philosophy that they had advanced during the present Symposium. They would cater for 24 - 25 students, 18 of whom would be, ideally, industrialists and six representatives of technical colleges. The Ministry of Education was looking very favourably on the idea of sponsoring arrangements whereby men from the technical colleges could work with industrialists on problems of this kind.

Mathematics was of tremendous importance. At the moment they were engaged in collecting a large number of production engineering problems involving mathematics, with a view to building up a syllabus based on the kind of mathematics needed to solve these problems. If it differed from the existing mathematics syllabus the latter should be thrown out, because students had not the time to study other than essentials. In the main, students would work hard trying to overcome the considerable difficulty some of them had with their mathematics, if they believed that it would be useful to them as production engineers.

Mr. F. Roberts (*U.K.A.E.A.*) felt that radio-active tracers were rather overdone, and regarded as the be-all and end-all of everything. As someone had said: " Measure what you can measure, and what you can't measure make measurable." Mr. Cherry had demonstrated that he could measure all he wanted by means already at his disposal, and that radio-active tracers would simply complicate the matter.

Mr. Hird's students had known the processes of mathematics, but had not known how to apply them. This could only come with a little experience. Probably none of his students had really thought they had the right answer!

Those who were interested in quantity production were, he felt, well able to take care of themselves, or ought to be. Research should perhaps be directed to getting a better product rather than greater quantity.

Mr. L. Webster (*Production Manager (Engineering) Distington Eng. Co. Ltd.*) sought clarification of the term " chip thickness ", as used in the Paper. There seemed to be some ambiguity. It had been referred to as feed/rev., maximum section, thickness per tooth and, of course, chip thickness.

Mr. Cherry said that chip thickness was the theoretical thickness of the chip in a square tool: it was not feed/rev. If one were using a tool with a plan angle on it and took the same feed/rev. chip thickness would be measured at right angles, which would not be the same as feed/rev. He would prefer " chip thickness " to " feed/rev.".

Mr. Webster asked whether this did not affect some of the practical applications, where one needed the actual chip thickness. Tool geometry would, in fact, affect this thickness.

Mr. Cherry agreed, but said that if one were to use tool life curves and derive a life curve for a certain chip thickness with a square tool, chip thickness would not, if one had a plan angle, apply.

Mr. T. N. Gillbe (*Lecturer in Production Engineering, Borough Polytechnic*), referring to the comparison made in the Paper between the automatically controlled miller and the conventional miller, said that 24 years ago he had worked as a boy in a machine shop using two-spindle and three-spindle machines, such as had been illustrated on the blackboard. He wondered how long he would have to wait before this became conventional. Cost comparisons should be made with that type of machine in mind and then the automatically controlled miller would not show up so well.

On the question of tool life with the profiling miller, he had had about 10 years' experience in producing aircraft ribs and components from solid billets. It was usually very complex, with the tool first running a straight line down the outside, then going in and cutting a notch, then a radius, and then going into the centre, and so on. The depth of cut was constantly changing. The mathematics involved were beyond

any normal engineer and would probably call for the services of an analogue computer. It was a very real problem.

They used pre-routing techniques and the tool change difficulty was not so great because one had to change templates anyway, but he wondered whether in view of the large number of variables involved, the suggested calculations could be made.

Mr. Cherry said that in using his illustrations, the automatically controlled miller and the conventional miller, he had taken actual cases which had been published. He had pointed out that in particular instances one or other could be made to look economical: that one really had to investigate the whole picture, and see whether the automatic machine would pay in the long run. He had wished to stress that, in view of the speed of operation, it was necessary to have sufficient work to keep the machines fully employed, and make certain that machine loading and production control was good.

He did not suggest that the calculations given would apply to every circumstance, but they did apply to many. Was the profile milling referred to being done mostly with the bottom, or the side?

Mr. Gillbe said that it varied as between the side and the end. One might be milling into pockets along walls. This had been shown in the film. At one moment it was cutting masses of material and at the next it was going round the edges.

Mr. Cherry said that short-cut methods might be possible. If one portion of the cutter were cutting all the time, it would be the portion that would wear and one would not bother about the rest. With regard to the constantly changing depth of cut, Mr. Cherry emphasised that they did not think that depth of cut had any effect on tool life, except insofar as it might cause greater deflection of the tool. Depth of cut merely spread the cutting load over another area.

The **Chairman**, in closing the discussion, said that Mr. Cherry had done them a remarkable service in presenting such a fine Paper and promoting such an interesting discussion.

UNIVERSITIES AS FACTORIES ? —

concluded from page 82.

it ideas flowed from below upwards. I think this is only half the story. In a good university, as in all flourishing human communities, ideas flow upwards and downwards and are modified and developed in the process until they are ready to be used as the basis for action. Wisdom does not repose exclusively in Council chamber, or Professorial Boardroom, or Students' Union but, if each is receptive and perceptive, results from the passage of ideas from one to the other. Dynamic equilibrium, not static, should be the aim.

It may be thought that I have strayed very far from my theme, from the analogy between a piece of steel being processed and a student being taught to some very amateur philosophising. The question mark in my title must be my excuse. Universities as Factories? Perish the thought: Factories as Universities? I leave that to the next Kirby lecturer.

Correspondence and comment on published Papers and matters of interest to production engineers are invited.

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THE PRINCIPLES AND PRACTICE OF TORQUE LOADING

by J. M. SHARMAN, M.A., G.I.Mech.E., Grad.I.Prod.E.

Senior Engineer,
de Havilland Aircraft Company,
Hatfield.

This Paper recently gained the South-East Regional Award for the best Paper submitted by a Student or Graduate of the Region.

Mr. Sharman was educated at Bedford School and St. John's College, Cambridge, where he obtained an honours degree in the Mechanical Sciences Tripos. He subsequently served a graduate apprenticeship at the de Havilland Aircraft Company at Chester, after which he was transferred to their main works at Hatfield as a Research and Development Engineer.

He spent a year on the editorial staff of "Aircraft Production" and has now rejoined de Havilland at Hatfield, as a Senior Engineer.

TORQUE-LOADING of the bolts on important mechanical or structural joints is established practice which, to meet increasingly stringent design requirements, is being more and more widely applied. It is now being specified for many non-structural joints—for example, by electrical equipment manufacturers to ensure adequate clamping of joints in essential circuits and hence their low resistance. Certain accessory manufacturers are also insisting upon torque-loading to ensure the correct and safe assembly of their products.

As any process comes into more common use it becomes increasingly important for a newcomer to the field to obtain at least a general knowledge of the subject, and this can often only be obtained by searching through the relevant literature, a tedious task in itself. In addition to this, articles have a tendency to deal with only one small aspect of the subject, and therefore do not in themselves impart an overall picture. The first part of this Paper has therefore been set out to give, in a very brief form, some of the background to the subject of torque-loading, what advantages may be gained from its use, and a summary of the various types of torque-loading tools commercially available.

This will serve as a background to the second section of the Paper, which deals with work carried out at the Hatfield factory of the de Havilland Aircraft Company into the problems which arise when using standard torque wrenches with special adaptors for

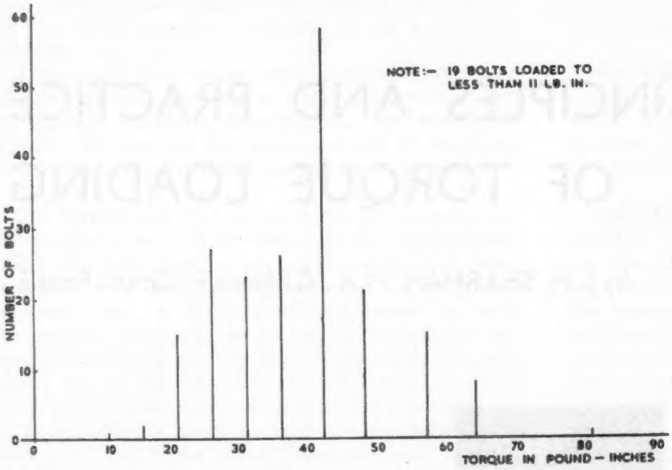


Fig. 1. Actual torque loads applied by an operator using hand tools to a batch of 2 BA countersunk-headed bolts.

reaching otherwise inaccessible nuts. It has been found on enquiry that many firms in the United Kingdom and overseas do not realise that such a problem exists or, if they do, then little is known of its extent or seriousness, or of any practical solution. It is therefore felt that the results of this investigation may well be of wide general interest. Reference will be made throughout this Paper to nuts and bolts though, of course, the principles discussed will apply to all forms of threaded assembly.

potential advantages

Because the use of non-standard equipment inevitably involves the outlay of capital, primary consideration must be given to the potential advantages to be gained from pre-tensioning a bolt to a given figure. One of the most valuable of these is the obviously desirable fact that whether or not the correct figure is being used, at least its value is known, and it can be varied by a definite amount should this be found necessary. The very questionable factor of having to rely on the skill and integrity of an operator for the consistency and tightness of all the nuts on a joint is thereby eliminated.

The torque applied by hand varies considerably from operator to operator, and the effect of this is made even worse if the bolts are to be assembled with different sealing or lubricating compounds. Even an individual operator, given a large number of nuts to tighten, may easily vary the torque which he applies throughout the run. "Standard" lengths of spanner do not help to any great extent because the variation of physical strength from one operator to another reduces their effectiveness.

A further consideration is that in fact it is usually the inspector who determines the final torque figure, because in most cases he will insist on moving the nut just a fraction during checking. The net results can be quite astonishing, as shown in Fig. 1. This shows the torque to which 216 2BA nuts were tightened on an assembly. They were loaded by a skilled operator using a "standard" spanner, and checked by an inspector, and although the expected Gaussian distribution is well marked, the overall scatter of torque is from less than 10 to more than 80 lb. in. Bolts assembled in test pieces under similar conditions to those in the component were tested to failure, and this occurred in some bolts at an applied torque as low as 70 lb. in. It will be seen that this is potentially extremely dangerous, especially as in this particular case the fracture of any one bolt in the assembly would have resulted in its head being drawn into the compressor of a jet engine. The pre-tensioning of these bolts to a known safe figure was an obvious necessity. The introduction of torque wrenches had a secondary advantage in that it appreciably decreased the overall production time for the assembly, because doubt was eliminated in the minds of both operator and inspector as to the condition of any one bolt relative to any other.

Any joint can therefore be taken which is particularly susceptible to fatigue, or which transmits an important stress pattern, and the tensions in the bolts at that joint adjusted to give the most favourable conditions for increasing the life or efficiency of that section of the structure.

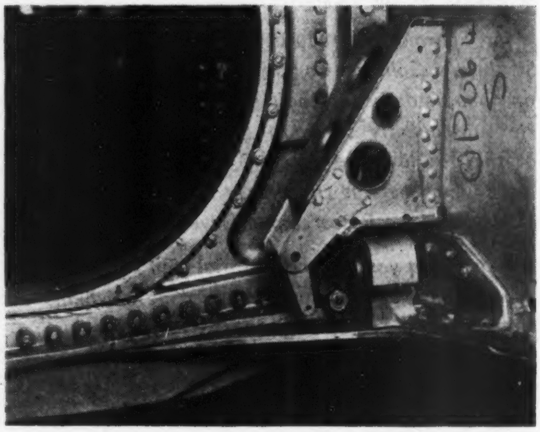
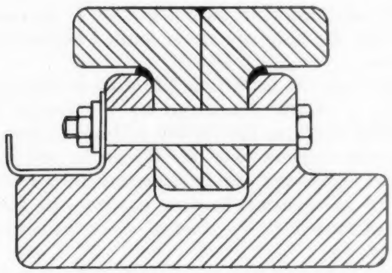
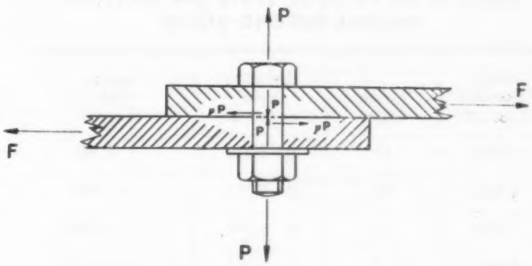


Fig. 2. Inboard end of the wing skin to rear spar joint on the de Havilland Comet 4.



CROSS-SECTIONAL VIEW THROUGH THE COMET 4 REAR SPAR.

Fig. 3.



SIMPLE SHEAR JOINT.

Fig. 4.

A joint of this type, where fretting is an important consideration, is shown in Fig. 2. This shows the junction of the Comet 4 wing skin to the rear spar at its inboard end. Here it is important to transmit the final skin loads to the spars as smoothly as possible, and apart from applying anti-fretting compounds before assembly, the holes are reamed to close tolerances, close tolerance bolts are used and they are torque-loaded. This prevents any one point of the spar/skin assembly from being clamped together more tightly than any other, and thereby from carrying more than its fair share of the oscillating shear load.

Another rather different case, and one which is a good example of circumstances in which an operator would almost certainly cause trouble if left to his own devices, occurs during the detail assembly of the Comet rear spar, a cross-section through which is shown in Fig. 3. Here the spar web fits into a channel in each spar-boom, and as can be seen, this produces a shear joint with the bolts acting solely as pegs. (The actual nuts can be seen in Fig. 2.) Because there is a small gap on either side of the web to facilitate assembly, it can be seen that, if the bolts were overloaded, it would result in the closing of the gap between the top corners of the channel section. In an extreme case the corners would fret on the web as the wing flexed in flight. All bolts through this particular joint are, therefore, torque-loaded to the low figure of 60-80 lb. in. to prevent this condition from arising. Because some of the bolts are ½ in. in diameter, it will be appreciated that an operator would almost certainly overload the joint if he used conventional methods.

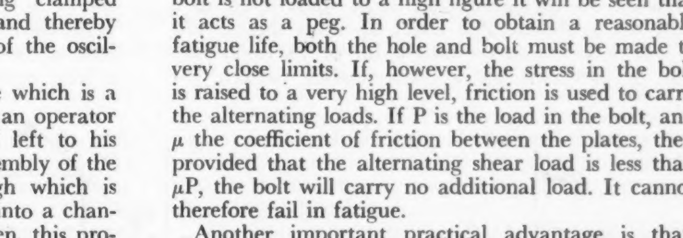
The most outstanding use of torque-loading is, however, the very considerable increase in the fatigue life of a joint if the bolts in it are very highly prestressed—a factor which is more widely used in the structural and mechanical rather than the aeronautical field.

For a shear joint the advantages of a high pretension are immediately obvious. In Fig. 4, which shows a simple shear joint held by one bolt, if the bolt is not loaded to a high figure it will be seen that it acts as a peg. In order to obtain a reasonable fatigue life, both the hole and bolt must be made to very close limits. If, however, the stress in the bolt is raised to a very high level, friction is used to carry the alternating loads. If P is the load in the bolt, and μ the coefficient of friction between the plates, then provided that the alternating shear load is less than μP, the bolt will carry no additional load. It cannot therefore fail in fatigue.

Another important practical advantage is that, because the bolt is no longer a peg, the dimensional tolerances of both the bolt and hole are no longer of prime importance. In many practical cases where weight is an important consideration these dimensions are, in fact, carefully maintained. This factor is especially important where the shear loads and coefficient of friction are open to doubt.

A more surprising result, perhaps, is the increase in fatigue life if highly pre-stressed bolts are used in a pure tension joint. This feature can be simply explained if one considers the example of a pure tension assembly held together by one bolt, in the manner illustrated in Fig. 5. If the cross-sectional area of the abutment faces is 10 sq. in. and of the bolt shank

Fig. 5. Single-bolted pure tension joint.



RESULTS OF FATIGUE TESTS ON AIRCRAFT ENGINE BIG-END BOLTS

Initial Pretension in pounds	*Number Tested*	*Operating Load in pounds*	*Average Life in cycles*
1,420	17	0—9,215	5,960
5,920	16	0—9,215	35,900
7,220	15	0—9,215	214,500
8,420	2	0—9,215	5,000,000+

Fig. 6

1 sq. in. then, if an initial pre-tension of 30 tons is applied to the bolt, the resultant compressive stress in the abutment faces will be 3 tons per sq. in. Because the total area of the abutment and bolt shank is 11 sq. in. a tension load can be applied to the complete assembly of 33 tons before the faces part. This load will, however, only increase the bolt tension from 30 to 33 tons per sq. in. Any subsequent increase in load beyond 33 tons will be carried solely by the bolt, with a consequently rapid increase in stress. For alternating loads of less than 33 tons, therefore, the bolt load is changed by less than 3 tons, that is to say, only 10% of the initial pre-stress. Because the ratio between the oscillating and mean stress levels in a bolt has a considerable effect upon its fatigue life, it will be seen that the fatigue life of a tension joint will be increased, for a given loading pattern, the higher the pre-tension in its bolts. This is, of course, provided that the bolts are never loaded beyond their yield points.

That this increase in fatigue life does in fact occur in practice, is clearly confirmed by the results of a study carried out into the failure of big-end bolts on aircraft piston engines (Fig. 6). It can be seen from this, that by increasing the pre-tension from 1,400 to 8,400 lb. for an identical loading pattern, the fatigue life was increased by a factor of approximately 1,000 : 1.

The important factor to be considered when loading a tension-loaded bolted assembly is the relative resiliences of the bolt and abutments. This is shown graphically in Fig. 7. To produce this effect a load-strain curve is drawn for the bolt core. (It is emphasised that it is a load-strain and not a stress-strain curve which is being considered.) If the relationship between the two is linear the line OA is produced. Hence, if the bolt is pre-tensioned to a load P, shown by the line BC, this will give a resultant elongation to the bolt of l_{B1}. This load will also deform abutment by a distance l_{A_1}. If the abutment load-strain curve, also assumed to be linear, is drawn and superimposed upon that drawn for the bolt, it will be represented by the line DE_1.

Any additional force F, tending to separate the abutments, will be shared between the bolt and abutments in the proportions F_{B_1} to F_{A_1}, the line RS_1 being drawn parallel to OA and at a distance equivalent to the load F below it. It can also be seen that a load equivalent to the initial bolt pre-tension can

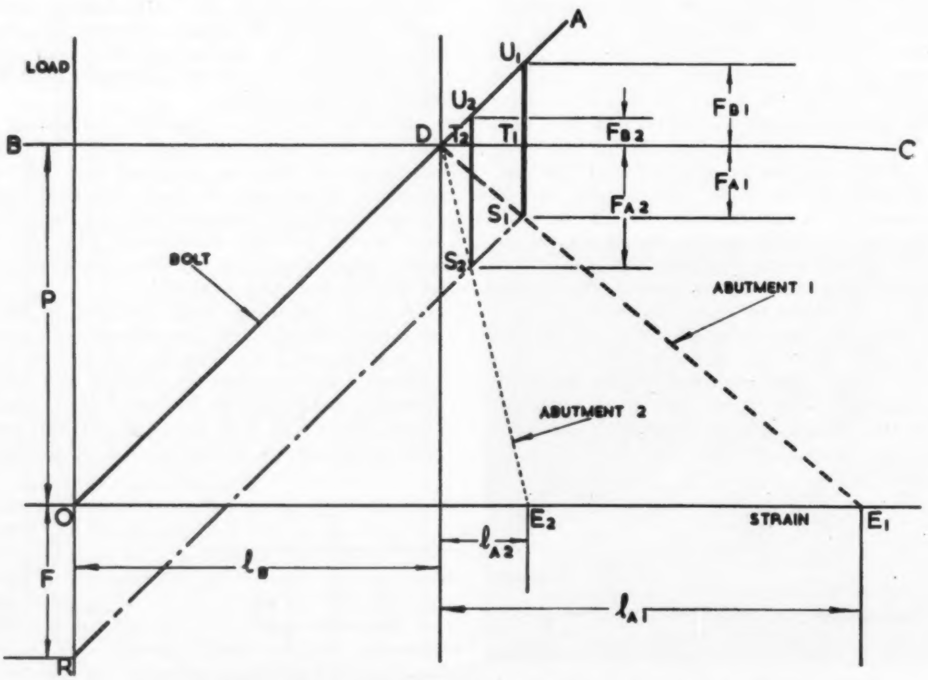


Fig. 7. Graph showing the effect of different abutment resiliency upon the distribution of an applied load between the bolts and abutments on a prestressed joint.

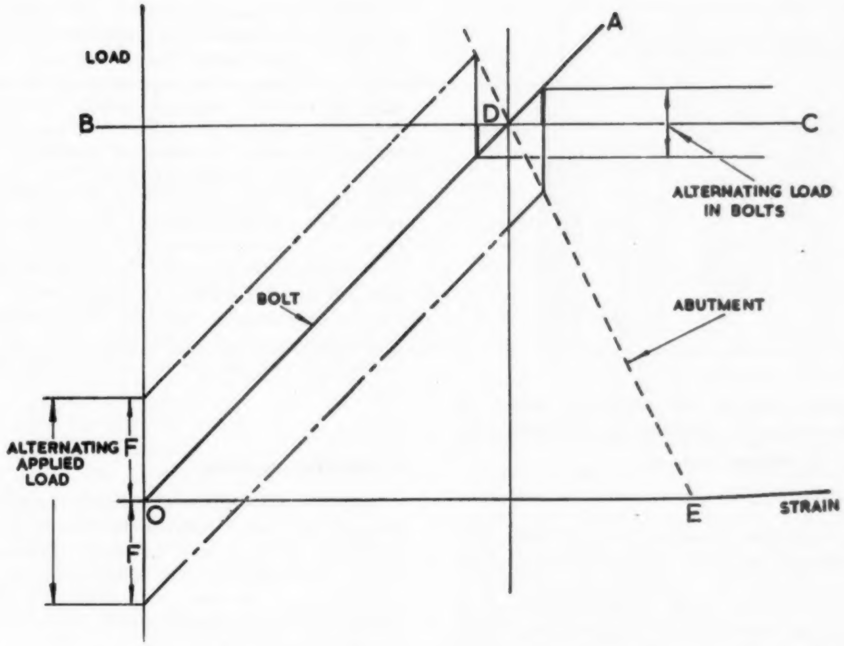


Fig. 8. Graph showing the reduction in the alternating load on a bolt for a specific alternating applied load as a result of pretensioning the assembly.

be applied to the assembly before the abutments part, and therefore that the higher this pre-tension the higher the maximum permissible load becomes. The less resilient the abutments relative to the bolt—obtained by increasing their cross-sectional area or raising the strength of their material—the less they will deform for a given pre-tension. This will have the effect of reducing the length l_A on the graph relative to l_B and hence, for a given pre-tension, the abutments will carry a larger proportion of any subsequent load than in the first case, as can be seen by considering the lines concerned with abutment 2 in the illustration.

If an alternating load is applied to the assembly, the load on the bolt itself will have a considerably smaller amplitude than this, as can be seen from Fig. 8. This also shows that the greater the initial pre-load the smaller will be the alternating/mean load ratio, and hence the fatigue life will be improved.

pretensioning methods

There are many different ways of applying a pre-tension to a bolt, the only really satisfactory method being to measure its extension under load. In most cases, however, this method is impossible to apply, due to inaccessibility. Under certain circumstances where short thick bolts are used, it is possible to drill a small hole along the axis of the bolt. A thin rod, which is secured at the threaded end of the bolt, is inserted into the hole and machined at the other end to be flush with the face of the head. On assembly, the nut is tightened until the bolt stretches sufficiently to draw the end of the rod below the surface of the head by a calculated amount.

Material deformation under load is also used in two other cases. One of these consists of inserting a conical washer between the nut and plain washer. The cone is compressed on assembly until it is flat. An alternative method is to use two washers, a thick one surrounded by a thin one. As the nut is tightened the inner washer deforms until it is of the same thickness as the outer one. At this point it becomes impossible to turn the outer washer, and by adjusting the radial thickness of the inner washer, this can be made to occur at a predetermined bolt load. These two methods ensure only that the nut is not slack; they do not guarantee that the bolt is not overloaded.

It will be seen that, due to the pitch of their threads, by tightening a nut on a bolt to a definite torque, it should be possible to produce a known tension in the bolt. This can be achieved by using an ordinary spanner and a spring balance, but this is a cumbersome and potentially inaccurate method, and torque wrenches have therefore been designed which are widely used in many industries. Before they can be used, however, the relationship must be found between the torque applied to the nut and the tension which it produces in the bolt.

The work done by an operator when tightening a nut on a bolt is absorbed in three ways—in stretching the bolt, in friction between the nut face and

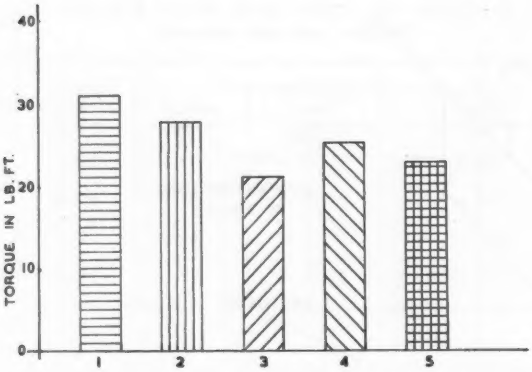


Fig. 9. Block graph showing the tightening torque to produce a specific tension in a particular bolt calculated from different formulae.

washer, and in friction between the nut and bolt threads. By taking values for the coefficients of friction at these points, and by compiling an equation—for example of the total work done—a theoretical relationship can be found between the torque applied to the nut and the tension load which it produces in the bolt. It is therefore theoretically possible to determine the torque required to produce any desired bolt pre-tension. There are many formulae in existence for calculating this torque value, but all depend to a varying extent on the effective radii of contact, both between the nut and bolt threads and between the nut and washer, and on the coefficients of friction between these pairs of surfaces.

The tightening torque to produce a given pre-tension in a specific bolt, calculated from formulae devised by different authors, varies considerably (Fig. 9). The first four of these results were calculated from some of these formulae, the fifth by using a simple rule-of-thumb method which states that

tightening torque = torque coefficient × bolt load × mean diameter of the thread

A commonly accepted value for the torque coefficient is 0.2. As is often the case, variations such as these leave the reliability of a purely theoretical approach open to question.

Because as much as 90% of the work done by the operator when tightening a nut can be lost in friction, it will be appreciated that a variation in the coefficient of friction, or in the radius of contact for either pair of mating surfaces, would profoundly affect the resultant tension in a bolt for one value of applied torque. Because the effective radius of the nut-to-washer surface is greater than that of the nut and bolt threads, any inaccuracies in manufacture of nut or washer, such as lack of flatness in the abutting faces, will have a considerable effect on the bolt load.

It is therefore advisable to produce a nut with the smallest possible effective contact radius. One where the bearing area is equal to the cross-sectional area of the bolt core is the ideal for, at this size, the stresses in the bolt core, in the nut and on the abutments are equal.

a different method

Another quite different method is available for narrowing the head friction tolerance. If the bolt is provided with a head of large dimensions and a recess is arranged in the bearing-surface so that it is reduced to a narrow ring, then the difference between the largest and smallest head friction moment is also reduced.

The effect of these designs can be most marked. For example, in a case where the mean nut bearing diameter was 1.8 times the diameter of the bolt shank, one would normally have to expect a scatter of 80% in the torque lost due to friction at this surface. However, this was reduced to 20% when a suitable annular surface was used. If the compression between the annulus and the abutment is too large for the abutment material, an additional washer may be used between the two. This washer should be large enough on the side which rests on the softer material, and of sufficient thickness, to transmit the clamping forces to a suitable area.

Friction between the threads, and between the nut and washer face, can be considerably reduced by careful manufacture of the components. Choice of suitable cladding materials and lubricants, bearing in mind the operational conditions of the assembly, will also have a marked effect upon the consistency and magnitude of the resulting pre-tension.

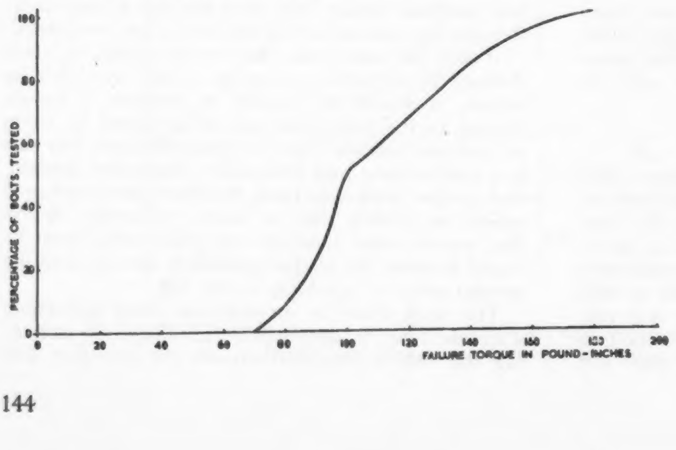


Fig. 10. Graph showing the torque required to cause failure to occur in 80 2 BA countersunk-headed bolts from three different batches fitted with stiffnuts (no assembly compound used).

Fig. 11.						AVERAGE FAILURE TORQUE IN LB. INS. OF 6 NUT AND BOLT ASSEMBLIES USING:—			
Bolt Diameter	*Bolt Material*	*Bolt Part Number*	*Nut Type*	*Nut Part Number*	*Thread Form*	*No Lubricant*	*'Duralac' Jointing Compound*	*Bostik Sealant 1753 red*	*Thiokol Sealant PR 1422 BT*
$\frac{5}{16}$ in.	Steel	A102/IG	Plain Steel	A103/GP	U.N.F.	389	310	471	590
$\frac{5}{16}$ in.	Steel	A102/IG	Thin Steel	A103/GT	U.N.F.	333	213	378	456
$\frac{1}{4}$ in.	Steel	A25/IE	Plain Steel	A27/EP	B.S.F.	294	146	280	251
$\frac{1}{4}$ in.	Light Alloy	A169/IE	Plain Light Alloy	A107/EP	U.N.F.	178	91	176	Not Available

All theoretical results must be substantiated by practical tests, and these confirm that, under normal conditions, a wide scatter does occur in the torque required to fail a nut/bolt assembly. An extreme case is shown in Fig. 10. This shows the percentage of all bolts tested which failed at or before a certain torque. The familiar Gaussian curve can be produced from this, a mean figure determined, and after applying the necessary safety factors, a satisfactory torque value can be established.

Practical tests also show very clearly the marked effect of different assembly compounds on the torque required to cause the failure of otherwise identical assemblies. Typical figures appear in Fig. 11. The tests also reveal the disturbing factor of the sometimes considerable variation between different batches of bolts to the same specification, and also the occurrence of sub-standard bolts. It is felt that some simple method of testing all bolts before they leave the manufacturer could easily be devised. This could perhaps be based on the relationship between the tensile strength and the hardness of materials, using one of the forms of magnetic hardness testing apparatus currently available. If this were done, then torque loading would be far more trustworthy for general use.

The theoretical results mentioned above presuppose that failure of the assembly will occur across the shank or thread core of the bolt, whichever is the smaller. If, however, circumstances lead to failure of the bolt head, or the nut or bolt threads, due to using a small or countersunk headed bolt, or a thin nut for example, then it is extremely difficult to calculate a satisfactory torque load for the assembly. Under these circumstances experimental methods must be used.

commercial tools

Torque wrenches themselves take many different forms, the simplest of all being the beam spanner. In this type the handle is made of a flexible material, and it will be appreciated that the deflection of any point along the beam will be proportional to the torque at the spanner drive square. This deflection is measured in some way, for example by a rigid pointer that is fixed to the spanner head and whose other end is free to move across a scale. As can be seen this group are simple tools and are, on the whole, fairly cheap.

Another type which is dependent on deflection for its readings measures the twist in a pin. This is rigidly secured at one end to the head of the wrench, the socket being fixed to its other end. The twist of a given length of the pin is magnified by a beam inside the spanner handle and this operates a clock mechanism. The clock on this type of instrument may be of the continuous-reading kind, or may record the maximum torque applied. In some cases both of these facilities are incorporated.

One disadvantage of this group of wrenches, especially when dealing with large torques, is that the body of the spanner itself deflects, as in a beam wrench, and this leads to inaccuracies. This fault has been overcome in one make of wrench by having the handle as a separate unit from that containing the magnification arm and clock mechanism. Here, of course, any convenient shape or length of handle may be employed.

Many companies feel that dial-reading torque wrenches throw too much responsibility on the operators and inspectors for general shop use. Wrenches which can be pre-set to the required torque on a test-and-setting rig are therefore widely used. Tools of this type have a mechanism which prevents the

Fig. 12. A torque loaded joint of the Comet 4 structure illustrating the problem of accessibility that can arise in applying a torque wrench to some of the nuts.

Fig. 13. A group of extension sections designed by de Havilland for use with standard torque wrenches.

desired torque from being exceeded. A typical example is the Acratork torque wrench. This has a cam device in the spanner head, out of which a roller is forced against a spring in the handle when the torque on the cam reaches a sufficiently high figure. Fixed to the cam is a normal socket drive peg, the spanners being available in various sizes for right-handed, left-handed or dual operation.

For torques of 1,000 lb.ft. or more, where it becomes impracticable to use manual methods, hydraulic torque generators are available. These are specially made to suit individual cases, for example, torque-loading aircraft propeller retaining nuts.

An innovation to assembly line practice, which gives a certain degree of torque-loading consistency, is the pneumatic nut-runner or screwdriver. These have a turbine similar to that used in a normal air-operated drill, which drives the socket or screwdriver bit through a spring-operated clutch unit. The compression of this spring can be adjusted to vary the torque at which slipping occurs. One of the main advantages of this tool is the great speed with which large numbers of nuts can be tightened, but critical adjustment of the torque is difficult, and unless compensating units are fitted, the tool is often dependent on the factory airline pressure.

a different problem

One of the greatest problems which arise with these tools is to know the relationship between the final torque on the nut and the pre-set torque at the clutch unit. This unit is usually set by hand to break at a given torque, either on a setting rig, or with a torque wrench. When in use under power, both the nut-runner mechanism and the nut are travelling at speed, and when the nut meets the abutment, a torque will be applied, due to the momentum effect, in addition to the clutch unit breaking torque. This momentum effect will naturally depend upon the mass of moving parts, the speed at which the nut is travelling when it meets the abutment, and on the resiliency of the assembly. To the best of the writer's knowledge this problem has never been studied in any detail, though it is fully appreciated by the manufacturers of the tools. "Drawing-torque", that is, where the nut is tightened under some constant restraining force, such as compressing a spring, has been quoted by one supplier as being as low as 2/5 of the "free-running-torque", where the nut has a lubricated free movement on a bolt of sufficient length to allow the equipment to reach its maximum speed before the nut meets the abutment. This does indicate that pneumatic nutrunners, at least of this type, should not be used where accurate control of torque is essential unless extreme precautions are used.

There are many other types of torque wrenches, torque screwdrivers and torque multiplication gearboxes, each of which has its own particular merits, and they are manufactured in many countries.

limitations of standard tools

As with many things in industry, however, standard tools cannot be used in many situations, and torque loading is no exception. It is often found that the majority of nuts can be tightened by commercial equipment, but that occasionally, due to accessibility difficulties—a problem which presents itself more often when repair work has to be carried out—adaptors must be used, such as those shown in Fig. 13. Unfortunately these introduce further complications. It was found by the de Havilland Aircraft Company during investigations into this matter, that whereas a torque wrench itself may keep within approximately $\pm$ 1% of its set torque, tolerances of $\pm$ 20% were not unusual when extension sections were used, even if the spanner setting itself and the relative positions of the extension section and spanner were unaltered. The design tolerance on the figures quoted for torque loads to be applied to bolts on the assembly line was $\pm$ 5%, and it was therefore necessary to find a remedy.

It should be noted that although this Paper hereafter deals specifically with Acratork torque wrenches, this is only for convenience. The principles involved apply to all makes of torque wrench when extension sections are used with them, as has been proved by practical tests. Certain makes of wrench are designed with their "break" mechanism situated at a point along the handle away from the nut-driver, and these must be treated as a normal wrench fitted with an extension section.

Solution of the problem is simple when it is remembered that torque is the product of the applied load, and the perpendicular distance from the point of application of the torque to the line of action of the load. The usual units of measurement in this country are pound-inches or pound-feet. When a torque-wrench of the Acratork type is used in the manner for which it was designed no problems arise, because the "torque axis" of the wrench is directly in line with the axis of the bolt which is being loaded. In these circumstances the torque figure remains constant, because the load applied to the wrench alters in magnitude in direct proportion to the distance along the wrench-handle of the point of application of the load. As soon as these two axes are moved relative to each other, however, lever arm problems arise. It then becomes important where the wrench is held when applying the load, and in many cases the angle of application of this load relative to the handle. The possible variations which can be obtained could be serious, more than $\pm$ 70% having been obtained during practical tests.

The problem becomes clear if one considers the simple example of a wrench with a 10-inch extension section fixed to its head and in line with its handle. Assuming that the wrench has been set to a torque of 500 lb.in. at its head, this could be produced either by a load of 500 lb. applied to the handle at 1 inch from the head, or 50 lb. at 10 inches, as shown in Fig. 14.

Until the spanner "breaks", the spanner and extension section act as a rigid bar. The torque at the nut in case A is therefore :—

$$T_A = 500 \times (10+1) \text{ lb.in.}$$
$$= 5{,}500 \text{ lb.in.}$$

In case B, however, the torque is :—

$$T_B = 50 \times (10+10) \text{ lb.in.}$$
$$= 1{,}000 \text{ lb.in.}$$

It is seen that, without changing the setting of the wrench, or altering the length of the extension section or its position relative to the spanner, it is possible to produce a large variation of torque at the nut, solely by moving the point of application of the load along the spanner handle.

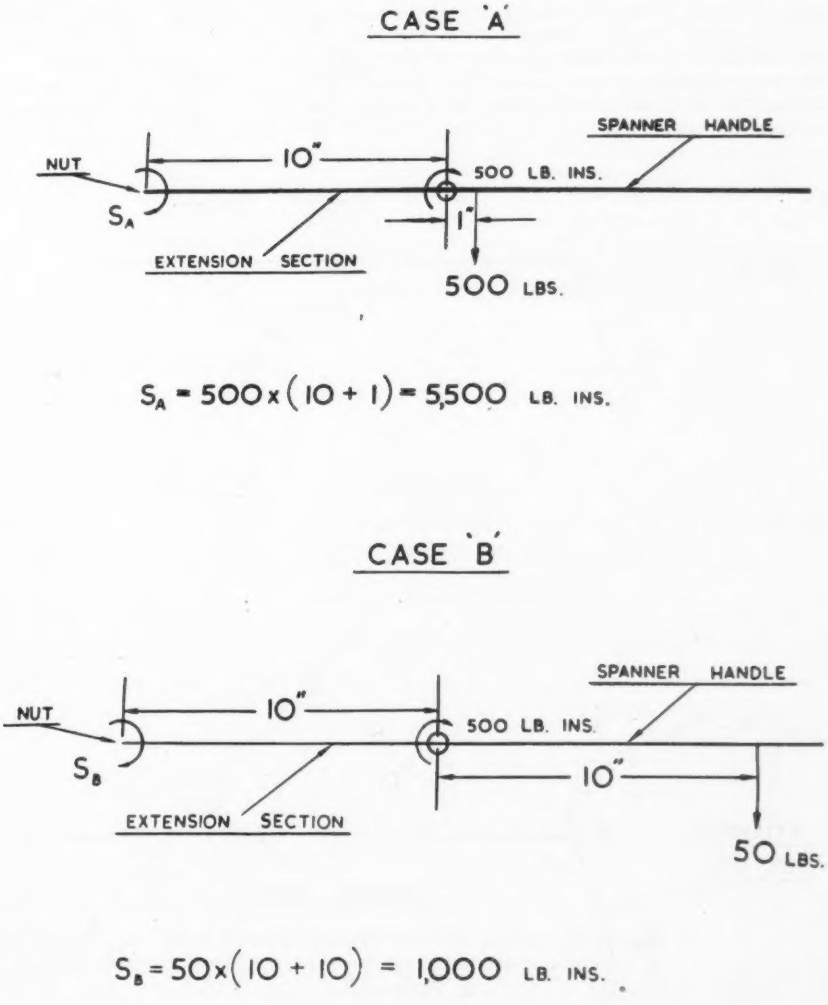


Fig. 14.

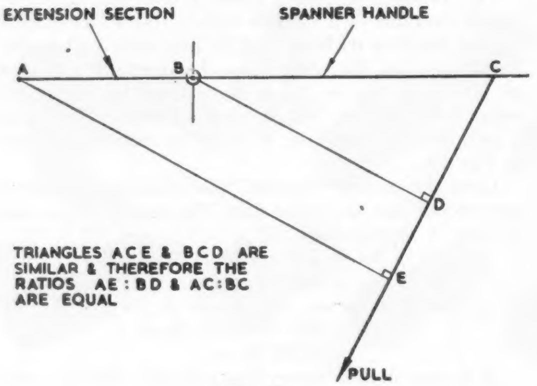


Fig. 15.

In the above cases it does not matter at which angle the load is applied relative to the spanner, because the extension section is in line with the spanner handle. The ratio of the effective lever arms (i.e. the perpendicular distances from the nut and spanner head to the line of action of the load) is therefore the same as that between the distance from the nut to the point of application of the load, and from the spanner head to this point. Fig. 15 illustrates this. If, however, the extension section is not in line with the spanner handle, then variations in the angle of application of the load will have their effect upon the torque at the nut, as can be seen from Fig. 16. In the upper diagram, because the perpendicular distance from the nut to the line of action of the load is less than the distance from the spanner head to this line, the torque at the nut will be less than at the spanner head. In the lower case the reverse is true, and it can be seen that if the extension section is not in line with the spanner handle, then the angle of application of the load as well as its point of application becomes important.

Both the position and angle of applied load factors can be incorporated in one general formula, the derivation of which is as follows:—

Consider the case where the load is applied to the spanner in the position and direction as shown in Fig. 17. The two actual extension sections may be considered as one "equivalent extension section".

Load applied to the spanner handle ... = P
Angle between the line of action of the load and a perpendicular to the spanner handle ... ... = Θ
Distance from the spanner head to the point of application of the load ... = x

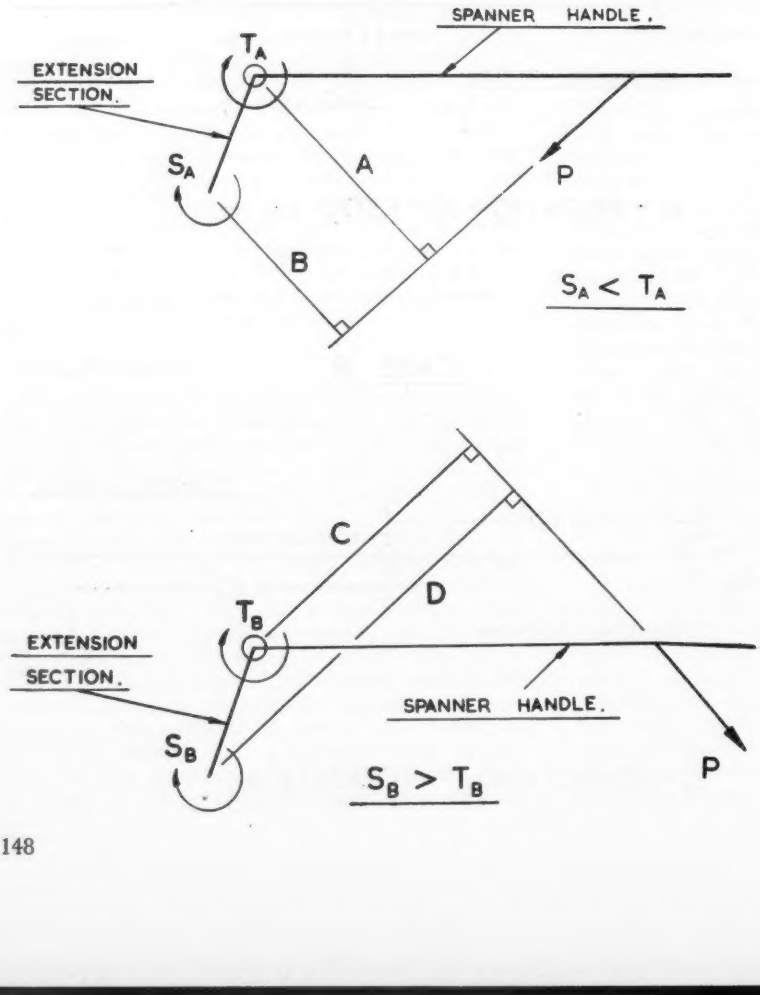


Fig. 16.

Angle between the equivalent extension section and the spanner handle ... = ϕ
Equivalent extension-section length ... = y
Set torque at the spanner head ... ... = T
Actual torque applied to the nut ... = S

Note :—All torques are measured in a clock-wise direction.

Taking moments about B

$$P = \frac{T}{BD} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

Taking moments about A ...

$$S = P.\ AE \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

From (1) and (2)

$$S = T.\frac{AE}{BD} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

From triangle BCD

$$BD = x \cos \theta \quad \ldots \quad \ldots \quad \ldots \quad (4)$$

From triangle AEG

$$AE = AG \sin \theta \quad \ldots \quad \ldots \quad \ldots \quad (5)$$

But

$$AG = FG - AF \quad \ldots \quad \ldots \quad \ldots \quad (6)$$

$$\therefore AE = (FG - AF) \sin \theta \quad \ldots \quad \ldots \quad (7)$$

From triangle CGF

$$FG = FC \cot \theta \quad \ldots \quad \ldots \quad \ldots \quad (8)$$

But

$$FC = BC + FB$$
$$= x + FB \quad \ldots \quad \ldots \quad \ldots \quad (9)$$

From triangle AFB

$$AF = y \sin \phi \quad \ldots \quad \ldots \quad \ldots \quad (10)$$
$$FB = y \cos \phi \quad \ldots \quad \ldots \quad \ldots \quad (11)$$

Substituting (11) in (9)

$$FC = x + y \cos \phi \quad \ldots \quad \ldots \quad \ldots \quad (12)$$

Substituting (12) in (8)

$$FG = (x + y \cos \phi) \cot \theta \quad \ldots \quad \ldots \quad (13)$$

Substituting (10) and (13) in (7)

$$AE = [(x + y \cos \phi) \cot\theta - y \sin \phi] \sin\theta \quad (14)$$

Substituting (4) and (14) in (3)

$$S = \frac{T \sin\theta[(x + y \cos \phi) \cot\theta - y \sin \phi]}{x \cos \theta}$$

$$\therefore S = T \left[1 + \frac{y}{x} (\cos \phi - \sin \phi \tan \theta)\right] \ldots \text{A.}$$

Two extreme cases of this formula are of particular interest :—

1. Where $\phi = 0$ deg. that is, when the nut is in line with the spanner handle but beyond the spanner head.
   In which case :—
   $$S = T \left[1 + \frac{y}{x}\right] \quad \ldots \quad \ldots \quad \ldots \quad \text{B}$$
2. Where ϕ = 90 deg. that is, when the nut is offset on a line perpendicular to the spanner handle through the spanner head.
   in which case :—
   $$S = T \left[1 - \frac{y}{x} \tan \theta\right] \quad \ldots \quad \text{C}$$

Thus, in case B, it can be seen that the only factor which affects the torque at the nut is the ratio of the equivalent extension-section length to the distance between the spanner-head and the point of application of the load; the angle at which the load is applied being of no consequence. However, in any other case, and in particular in case C, the angle at which the load is applied to the spanner-handle, as well as its point of application, becomes increasingly important. These factors can be shown in graphical form. (Figs. 18 and 19.)

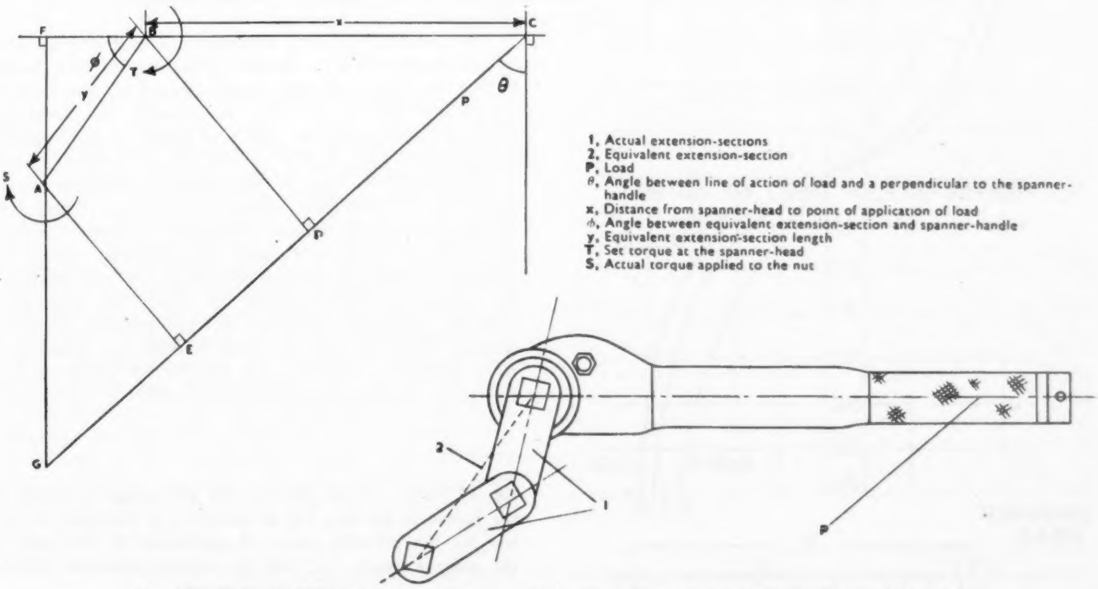


Fig. 17. Diagram illustrating a spanner to which two extension-sections have been joined in order to reach an otherwise inaccessible nut and (left) the equivalent diagram.
Courtesy of "Aircraft Production".

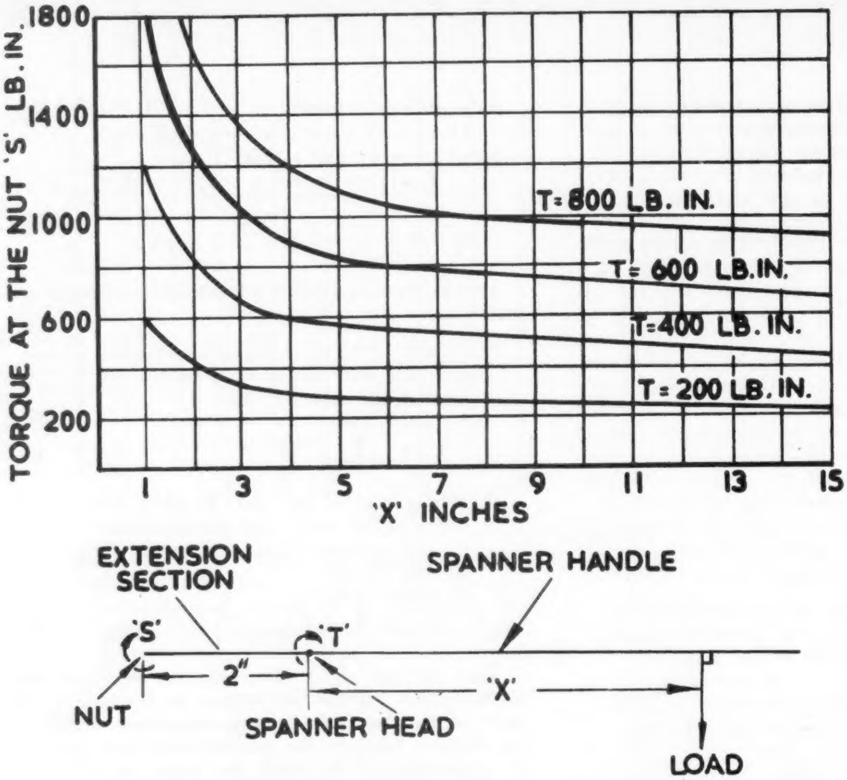


Fig. 18. (above). **Graph showing the resultant torque at the nut for varying points of application of the load to the spanner handle for different torque settings at the spanner head " T ", with the spanner/extension section geometry as shown.**

The formula proved extremely useful during the design work on the spanner attachments that were to be used to reduce the errors caused by the factors mentioned above, in that it showed the working limits in both angle of pull and point of application of the load. Two typical results are as follows :—

The graph in Fig. 20 shows the percentage variation in the resultant torque at the nut, using the spanner-extension section geometry as shown, when the angle of pull is varied, for different values of spanner length. It can be seen that for any particular tolerance, for example $\pm$ 5%, the allowable angular variation decreases as the spanner becomes shorter. Thus for an Acratork Model A4 spanner it is $\pm$ 10.8 deg., whereas for the Junior model, using the same extension sections, it is only $\pm$ $3\frac{1}{2}$ deg.

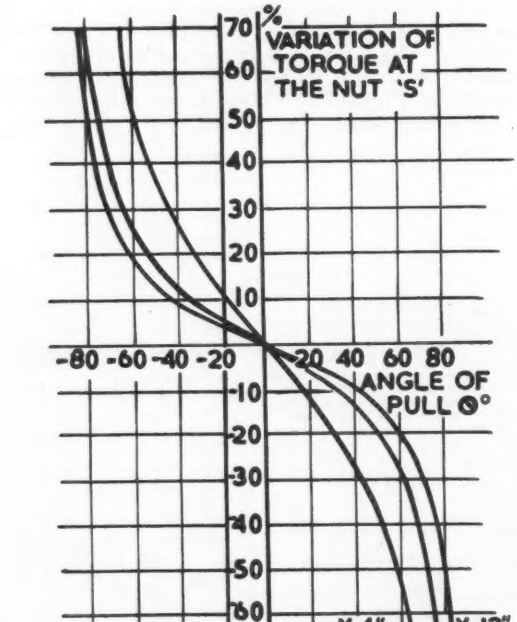


Fig. 19 (left). **Graph showing the percentage variation in the torque at the nut, due to variations in the angle of pull and for the differing points of application of the load to the spanner handle " x " for the spanner/extension section geometry as shown.**

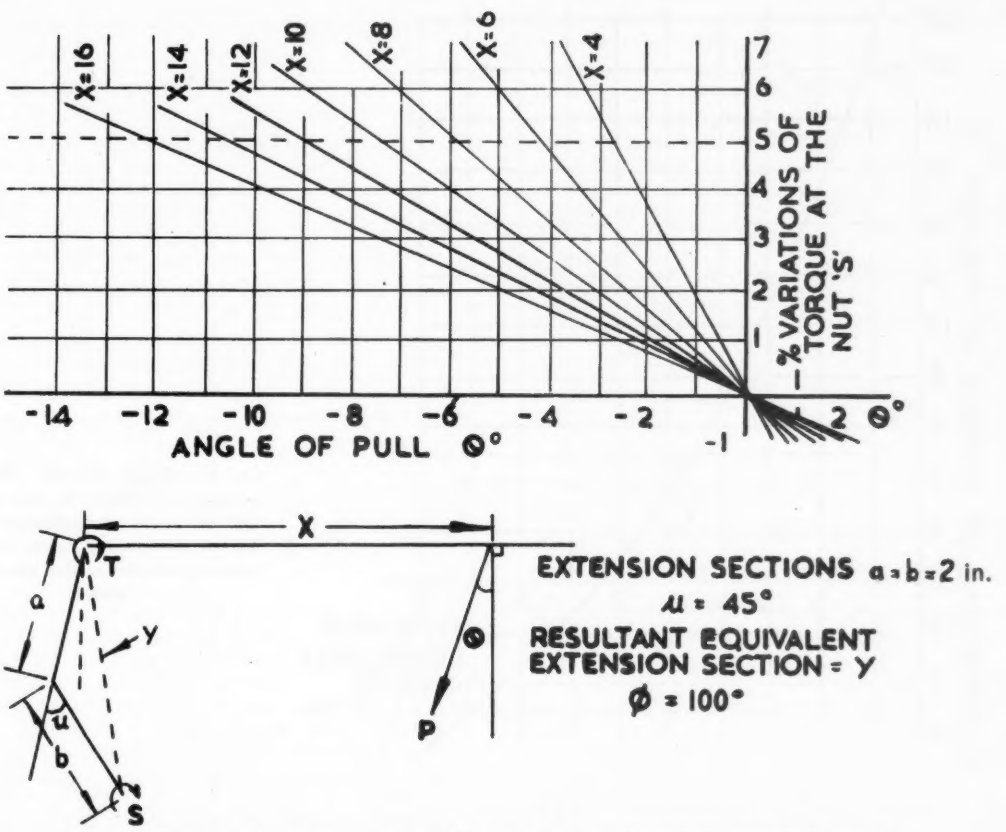


Fig. 20. Graph showing the percentage variation in torque at the nut due to variation in the angle of pull for differing effective lever-arm lengths X with the spanner/extension section geometry as shown.

The graph in Fig. 21 illustrates what happens when, with a constant angle of pull, the position of the applied load is varied from a nominal $7\frac{1}{4}$ in., for the spanner-extension section geometry shown. It will be seen that the torque tolerance of $\pm$ 5% is exceeded if the load is applied at less than 6.3 in. or more than 8.55 in. from the spanner head. Because the average width of a man's hand is 4 in., this can be seen to be a serious situation, especially as matters could be made even worse if errors due to variations in the angle of pull have an effect on the result.

The modifications to the standard spanner had therefore to ensure that the operator applied the load to the spanner at the same point and in the same direction as did the inspector when setting the equipment on the testing rig. Various methods were tried, including one which entailed applying the load at different points along the spanner handle to produce differing torques at the nut. It was finally decided to use a separate spanner for each setting, and to use a special handle attachment with each spanner which was used with extension sections. When in use the load is applied to the spanner by way of a peg in a square hole that is machined in an attachment secured to its handle, thereby eliminating one source of error. It should be noted that the handle which is fastened to the drive peg must be in a plane at right-angles to the spanner. This will then eliminate the effect caused by the width of a man's hand.

The more difficult source of error to eliminate was that caused by the load being applied at varying angles to the spanner handle. Here again a number of possible solutions were considered. The final design consisted of a cage which fitted round the hand and wrist of the operator and thereby reduced the possible angular variation in the direction of the load which he applied to within acceptable limits. The wristcage was designed so that it could be used to apply the load to the spanner handle either by pushing or pulling. Fig. 22 shows a complete assembly ready for use.

This equipment considerably reduced the variations in the resultant torque applied to the nut, but although the results were satisfactory for the larger tools and torque figures, low values were still difficult to obtain with any consistency. A critical evaluation of the

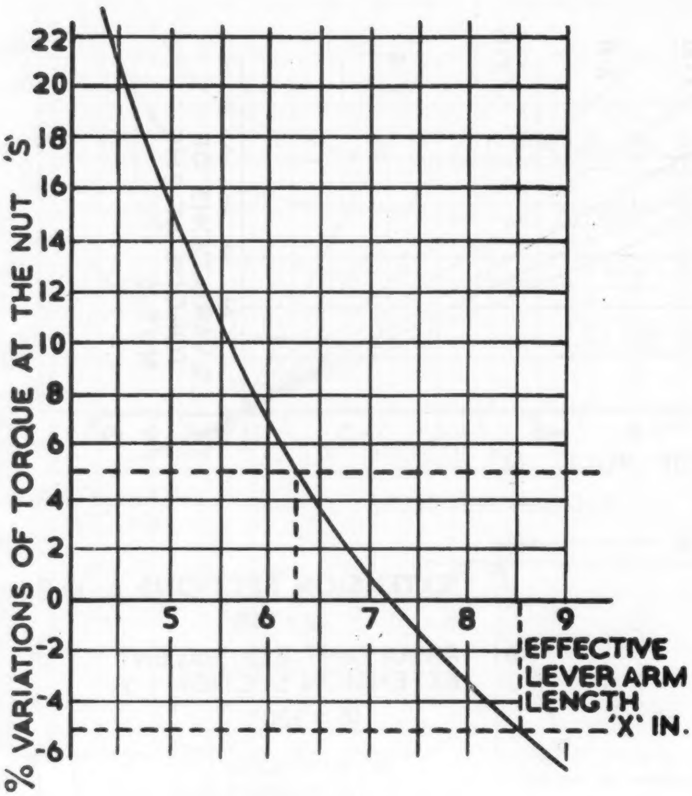


Fig. 21. Graph showing percentage variation in torque at the nut for different points of application of the load to the spanner handle with the spanner/extension section geometry as shown.

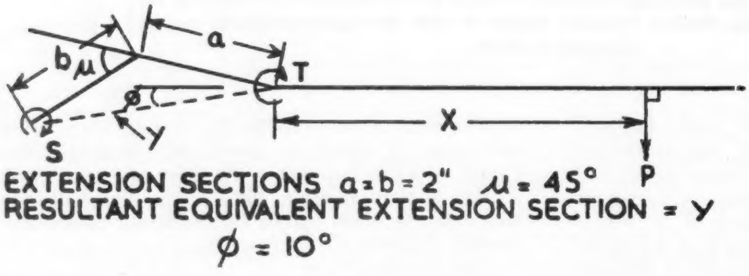
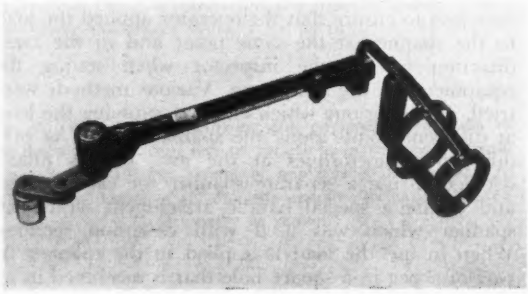


Fig. 22. (below). Torque wrench fitted with extension sections and a device for ensuring constant position and direction of pull.



equipment was therefore carried out, and further consideration given to the basic problem.

It was realised that a third possible source of error could be introduced by the operator twisting the spanner in addition to applying a direct load, as shown diagrammatically in Fig. 23.

In case A, the spanner is being used correctly, the applied load P producing a resultant torque S at the nut. In case B, however, a clockwise torque K is applied to the spanner handle, in addition to the direct load. This produces a force L at the spanner head which transmits a force M to the end of the extension section, and this gives a resultant anti-clockwise torque N at the nut, in opposition to the torque S. The reverse situation occurs in case C. In

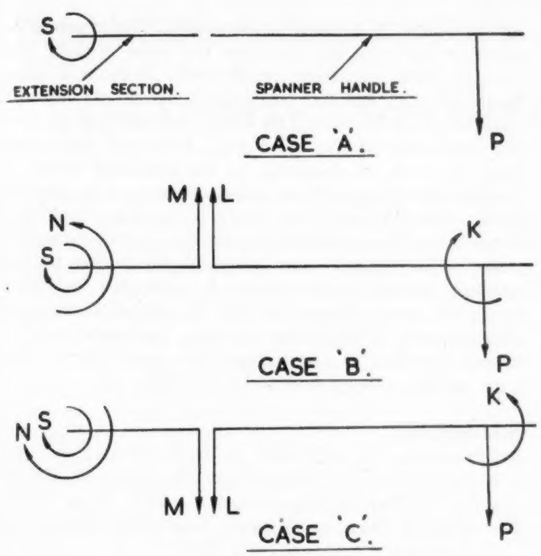


Fig. 23.

the early design of wristcage the operator's hand is not in line with the spanner handle, and therefore, any side load or twisting moment applied by him would inevitably produce this trouble. This "buckling torque" produces negligible errors when using a long torque spanner set for high torque loads and used with a short extension section, but it becomes increasingly important at the opposite extremes of these conditions.

Another factor which affects the torque at the nut is side load applied along the axis of the spanner handle. This is almost inevitable if open-ended extension sections are used, in order to keep the tool on the nut. The effects are small, however, and only become appreciable when using long extension sections with a large angle of offset for applying small torques.

These two factors can be added to the general formula as follows (Fig. 24):—

Buckling torque applied by the operator = B
Perpendicular load on the spanner head due to buckling torque ... ... = L
Perpendicular load on the extension section due to L ... ... = M
Resultant torque at the nut due to the buckling torque ... ... = N
Side load applied to the spanner by the operator ... ... = R
Torque at the nut produced by side load = V

For the buckling torque:—

Taking moments about C

$$L = \frac{B}{x} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (15)$$

Taking moments about A

$$N = M.y \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (16)$$

$$\text{But } M = L \cos \phi \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (17)$$

$\therefore$ substituting (17) in (16)

$$N = L.\, y \cos \phi \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (18)$$

Substituting (15) in (18)

$$N = B.\ \frac{y}{x} \cos \phi \quad \ldots \quad \ldots \quad \ldots \quad (19)$$

For the torque resulting from side loads:—

Considering triangle AFB

$$V = R.\, AF$$
$$= R.\ y \sin \phi \quad \ldots \quad \ldots \quad \ldots \quad (20)$$

By combining (19) and (20) with the original equation "A"

$$S' = S - N - V \quad \ldots \quad \ldots \quad \ldots \quad (21)$$

$$= T\left[1 + \frac{y}{x}(\cos \phi - \sin \phi \tan \Theta) - B\frac{y}{x}\cos \phi - R.y \sin \phi\right] \ldots \text{D.}$$

or by rearranging

$$S' = T + \frac{y}{x}\left[\cos \phi\,(T - B) - \sin \phi\,(T \tan \Theta - R.x)\right] \ldots \text{E.}$$

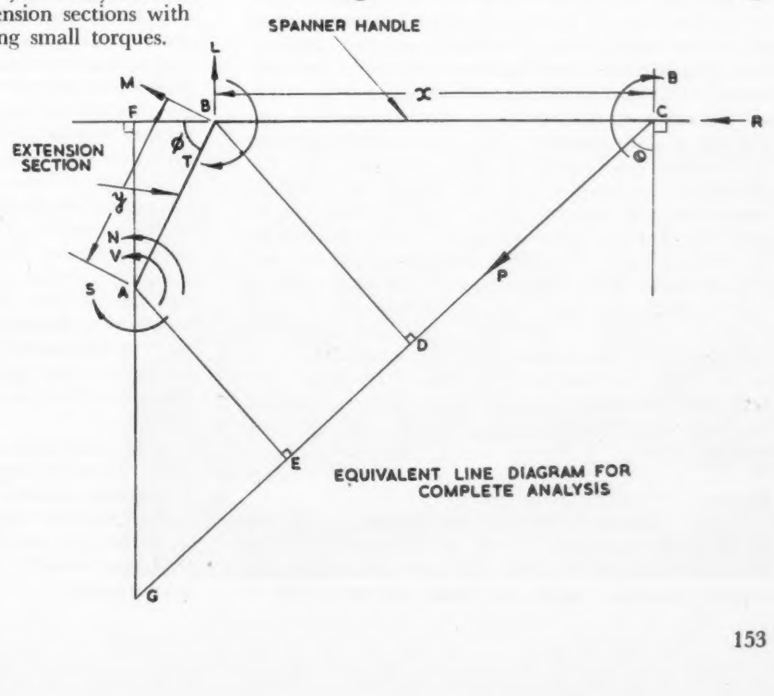


Fig. 24.

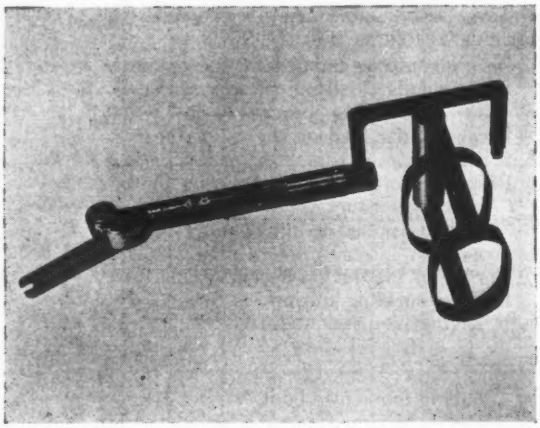


Fig. 25. A small torque wrench fitted with the revised type wristcage.

No practical method yet devised overcomes the effect of side loads on the spanner, but a new type of wristcage has been designed which removes the effects of buckling torques. The handle in this model has been re-positioned in line with the spanner handle, and to eliminate any twisting moment being applied to the spanner, the hand-grip consists of a rod enclosed by a loose-fitting tube. If the operator attempts to twist the spanner the tube rotates, the spanner itself remaining unaffected. Because it must be possible to use the wristcage to push or pull the spanner, it is necessary to have two drive pegs, one on either side of the hand-grip. Although the wristcage is more cumbersome in its modified form, it enables the design of the handle sleeve to be simplified. The sleeves are interchangeable and are located on the spanner handle by a socket-headed screw. This permits easy removal for access to the spanner setting mechanism. A complete assembly ready for use is shown in Fig. 25, and although the arrangement is far from perfect, particularly as a production tool, it has reduced the worst errors met with so far to approximately $\pm\ 3\frac{1}{2}\%$.

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PERA NEWS LETTER — continued

and machinery will be held on the ground floor of the Multi-Purpose Hall, which has a balcony seating 250 people. The Hall also contains a cinema projection room, a buffet, servery, stores, etc.

laboratory block

Extensive use will be made of the display area of the ground floor of the Laboratory block to stimulate the widest applications of PERA's research applications and technical investigations services in member-firms. A Conference Room, and offices for senior staff, are provided on the first floor, part of which is also a display and assembly area for conferences and exhibitions. Staff and facilities required for the industrial application of the results of PERA's researches into metal cutting, machine tools, metal forming, vibration, lubrication, etc., will be housed on the second floor. The third and fourth floors will accommodate work study engineers and staff engaged on investigations into factory layout, mechanical handling, planned maintenance, etc., in particular factories. The Association's rapidly expanding staff of translators will also be housed on these floors. The fifth floor consists of drawing offices, film and recording studios and facilities for preparing and printing publications.

library

PERA Library is already the largest specialised production engineering library in Europe, and when the new library is occupied, the collection of research reports, journals, books and trade literature will be still further expanded. Books will be stored on open racks, and trade literature in specially designed cabinets. A mezzanine gallery approached by a dual staircase is provided on three sides of the library and carries book racks, trade literature cabinets, four reading rooms, and sorting area.

The Research Applications and Technical Investigations Building represents a vitally important addition to the facilities of the Association, and will undoubtedly play a major role in extending the range and scale of assistance available to members in cutting production costs at every stage of manufacture from pre-production planning to the despatch of the finished product. Staff concerned with these activities are already investigating members' technical problems at the rate of more than 4,000 per annum. In many companies this assistance has extended over periods of several months, and growing numbers of member-firms are also retaining PERA staff for regular monthly visits to deal with specific types of problem. Because of the difficulties experienced by many members in finding suitably qualified and experienced staff at short notice, PERA is also fulfilling another important function by providing additional technical capacity when members' staff are temporarily overloaded.

The completion of the new building at the end of 1961 will make it possible both to expand still further all existing services, and to introduce the new services needed to meet members' growing needs for technical assistance in solving the increasingly challenging problems which are arising in all forms of manufacture.

Quarterly Newsletter to the Institution

PERA has always devoted a significant part of its efforts to promoting better utilisation of the new and improved techniques developed in the Association's own laboratories and those secured through an extensive network of communications with other laboratories and factories throughout the world. Services such as the Mobile Demonstration Unit, the Film Production Unit, Abstracting and Translating Services, Special Courses, Liaison Activities, etc., have often been of considerable assistance to members in reducing production costs and increasing output. Nevertheless, the Council and staff have not been satisfied and certainly not complacent about the speed and effectiveness with which the gap between research and practical application is being bridged.

two-stage building scheme

When the main Research Block (opened by Lord Chandos in 1958) was planned, it represented the first part of a building scheme which it was intended should be completed in two stages; the first stage being the main physical research building, and the second stage a building or buildings to house staff and facilities for the application of physical research results, and the carrying out of general research and special investigations over a wide field of production activities.

After a careful review of the facilities and accommodation available for staff concerned with the application of research results, and with improving production efficiency by means of work study, critical surveys of production techniques and equipment, design of special purpose equipment, etc., it has been decided to proceed with the second stage of the building scheme by erecting a Research Applications and Technical Investigations Building. The building is now in course of construction at PERA, Melton Mowbray.

The building will provide:

(a) laboratories, model workshops and offices equipped to deal with the problems of effectively applying research results to the solution of individual problems arising in member-firms;

(b) a multi-purpose hall for exhibitions, conferences, lectures, demonstrations, films, etc.;

(c) a comprehensive central library to serve research applications and technical investigations engineers as well as member-firms direct;

(d) laboratories and model workshops for work study and works engineering investigations into mechanical handling, factory layout, production techniques and equipment, etc.;

(e) design and drawing offices for staff engaged on the design of production plant and equipment, new and improved products, tools, jigs and fixtures, automation equipment, etc.;

(g) stores, offices and other accommodation for research applications and technical investigations staff.

The cost of the new building will be approximately £450,000. D.S.I.R. has agreed to make a capital grant of £100,000 towards this cost, and it is proposed to raise the major part of the balance through personal visits to companies using PERA services.

Further details of the building are given below:

multi-purpose hall

Exhibitions and demonstrations of production techniques, machine tools and other manufacturing plant

(concluded on previous page)

PERA's new Research and Applications and Technical Investigations Building, which is now in course of construction.

NEW BRITISH STANDARDS

Copies of the following British Standards, recently issued, may be obtained from the British Standards Institute, 2 Park Street, London, W.1, at the prices stated.

Supplement 1: 1960 **to B.S. 546 Two pole and earthing-pin plugs, socket outlets and socket outlet adaptors for circuits up to 250 volts.**
Supplement 1: Plugs made of resilient material. 4s. 0d.

Supplement 2: 1960 **to B.S. 1363 Two-pole and earthing-pin fused plugs and shuttered socket outlets for a.c. circuits up to 250 volts.**
Supplement 2: Plugs made of resilient material. 4s. 0d.

B.S. 3293: 1960 **Carbon steel pipe flanges (over 23 inches nominal size) for the petroleum industry. 12s. 6d.**

B.S. 3294: Part 1: 1960 **The use of high strength friction grip bolts in structural steelwork. General grade bolts. 3s. 0d.**

B.S. 3295: 1960 **Unit heads (slide type). 5s. 0d.**

B.S. 3296: 1960 **Safety requirements for domestic electric hair dryers. 6s. 0d.**

B.S. 3297: 1960 **High voltage post insulators. 10s. 0d.**

B.S. 3317: 1960 **Mild steel forged triangular lifting eyes for use on wire rope pulley blocks with a lifting capacity of 60 tons or more. 5s. 0d.**

B.S. 3326: —— **Portable carbon dioxide fire extinguishers. 4s. 0d.**

NEW AIRCRAFT STANDARDS

B.S. F 112: 1960 **Twisted and cabled flax cords for aeronautical purposes (replacing B.S. F 35 Section one). 2s. 6d.**

B.S. F 113: 1960 **Buoyant cotton cord for aeronautical purposes (replacing D.T.D. 767). 2s. 6d.**

REVISED BRITISH STANDARDS

B.S. 137: 1960; **B.S. 250:** 1960; **B.S. 466:** 1960; **B.S. 469:** 1960; **B.S. 693;** 1960; **B.S. 919: Part 1:** 1960; **B.S. 1001:** 1960; **B.S. 1344: Part A1:** 1960; **B.S. 1523: Section 2:** 1960; **B.S. 2062: Part 2:** 1960; **B.S. 2573: Part 1:** 1960; **B.S. 2634: Part 1:** 1960.

REVISED AIRCRAFT STANDARDS

B.S. 5 F 15: 1960; **B.S. 4 F 31:** 1960; **B.S. 5 F 32:** 1960; **B.S. 4 F 34:** 1960; **B.S. 5 F 35:** 1960; **B.S. 2 F 54:** 1960; **B.S. 2 F 58:** 1960; **B.S. 2 F 59:** 1960.

AMENDMENT SLIPS

Please order slips by quoting the reference number (PD...) and not the B.S. number.

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STANDARD WITHDRAWN

B.S. 1002: 1941 **High tensile brass bars and sections (suitable for forging) and forgings (not suitable for soldering).**

ISO RECOMMENDATIONS

Publication 100. Recommended methods for the measurement of direct interelectrode capacitances of electronic tubes and valves. £1 2s. 6d. Postage 2s.

Publication 113. Classification and definitions of diagrams and charts used in electrotechnology. 6s. 9d. Postage 1s. 6d.

ISO/R 136 Simple torsion testing of steel wire. 2s. 3d.

I.E.C. PUBLICATION

Publication 43. Recommendations for alternating current watt/hour meters. 18s. 0d. Postage 2s. 0d.

BINDERS FOR "THE PRODUCTION ENGINEER"

The Institution is able to supply the "Easibind" type of binder, in which metal rods and wires hold the issues in place, and which is designed to hold six issues.

It will be found that copies of "The Production Engineer" can be quickly and simply inserted into this binder, without damage to the pages, and that binding six issues at a time, instead of twelve, will facilitate easier reference and handling of the volumes.

The binders may be obtained from: The Publications Department, 10 Chesterfield Street, Mayfair, London, W.1, price 10/6 each, including postage. Date transfers, for application to the spine of the binder, can be supplied if required, price 6d. each. (Please specify the year required.)

NEW YEAR'S HONOURS

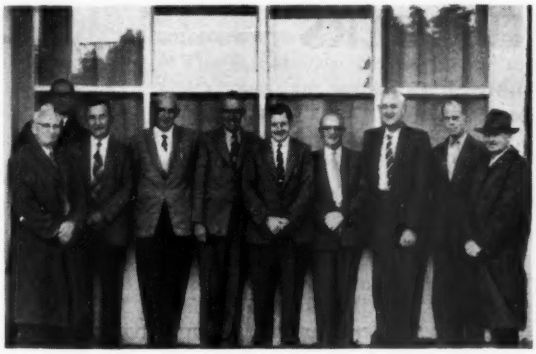
The Institution is pleased to record the inclusion of the following members in the New Year's Honours List:

C.B.E.: **Mr. J. R. Pheazey,** Vice-Chairman and Joint General Manager, Standard Telephones & Cables Ltd.

M.B.E.: **Mr. F. Baker,** Assistant Works Manager, Reyrolle & Co. Ltd.

Mr. C. J. Tirrell, Principal, Crewe Central College of Further Education.

NEW ZEALAND MEMBERS' TOUR



Members of the New Zealand Section and their wives paid a weekend visit, last November, to the Geo-Thermal Plant at Wairakei, and enjoyed an extremely interesting tour. The photograph above includes (from right to left): Mr. H. S. Weston; Mr. W. Moore; Mr. J. C. Fantham (Section Chairman); Mr. H. K. Pickering; Mr. A. F. Noutch (Hon. Secretary); Mr. J. E. Lissaman; Mr. H. R. Holmes; Mr. A. J. Lee; Mr. A. J. Holmes; and Mr. H. B. Robertson.

WALES REGIONAL DINNER

The second Annual Dinner of the Wales Region was held on 4th November, 1960, in Swansea. The principal guests included the President of the Institution; Mr. R. B. Southall, C.B.E., M.I.Prod.E.; the Mayor of Swansea; the Chief Constable of Swansea; and representatives of the I.Mech.E. and I.C.W.A.

Mr. Southall, in his address, referred to the changing pattern of industry in South Wales, and to the tremendous industrial potential of the area. There were great opportunities for The Institution of Production Engineers at all levels to co-operate in training schemes, and to bring influence to bear for changes where they were necessary to meet fresh needs, so that the new industries should have production engineers available with the crafts and skills required.

The President gave a stimulating talk on future Institution policy, and the Region looks forward with anticipation to his remarks bearing fruit.

The Region's thanks are expressed to the Swansea Section Committee for arranging such an enjoyable evening.

Members and guests in the photograph below are: (seated left to right) Mr. G. Whittam, Swansea Section Chairman; the Mayor of Swansea; Mr. W. H. Bowman, Wales Regional Chairman; Mr. G. Ronald Pryor, Institution President. (Standing left to right) the Chief Constable of Swansea; Dr. Stone; Mr. W. F. S. Woodford, Institution Secretary; Mr. P. H. Burton; Mr. R. B. Southall; and Mr. G. R. Faulks, Cardiff Section Chairman.

RETIREMENT OF MR. JOHN HORN, M.I.Prod.E.

Because of ill-health, **Mr. John Horn** has relinquished his executive directorship of The Forgrove Machinery Co. Ltd., but will retain his seat on the board for a further two years in an advisory capacity.

Mr. Horn has been the Company's Works Manager and Works Director for the past 28 years, being responsible during that period for the production of the firm's wrapping machinery and for the development and expansion of their factories in Leeds and Gateshead.

He is a founder member of the Yorkshire Section of the Institution, is a former Hon. Secretary and a Past Section President. He is also a Past President of the Leeds Association of Engineers and has served on its Council since 1935. He has had close connections with the Leeds College of Technology, being a member of the Mechanical Engineering Advisory Committee, and is also a Governor of Foxwod and Parkland Schools.

Mr. Horn's many friends throughout the Institution and the profession generally will wish him well in his retirement.

SHREWSBURY DINNER-DANCE

The Section's eighth Annual Dinner-Dance, held on 11th November, 1960, was again highly successful. This happy group includes Mr. H. F. Hodgson, C.B.E., Chairman and Managing Director, Joseph Sankey & Co. Ltd.; Mr. T. W. Elkington, Midland Region Chairman; Mr. J. Silver, Birmingham Section Chairman; and Mr. S. L. Robinson, Shrewsbury Section Chairman, with their ladies.

NEWS OF MEMBERS

Mr. J. Ayres, Member, Managing Director, Simms Motor Units, Finchley, has been elected Deputy Chairman of The Institution of Works Managers.

Mr. L. R. Beesly, Member, formerly Superintendent Director, R.S.A. Factory, Enfield, is now Director General of Aircraft Production, Ministry of Aviation.

Mr. D. B. Bowen, Member, has been appointed Sales Director of Stanley Howard, Birmingham. Before this appointment Mr. Bowen was Sales Manager, and previous to this, he was 24 years Midland Area Manager for E. H. Jones (Machine Tools) Ltd.

Mr. H. E. Drew, Member, Director of Electronic Production, Ministry of Aviation, has been re-elected Honorary Treasurer of The Institution of Works Managers.

Mr. J. G. Noble, Member, Chief Engineer, has been appointed a Special Director of Snow & Co. Ltd., Sheffeld. His official position will now be Works Director.

Mr. M. Seaman, Member, has been appointed Head of the Production Engineering Department at the Loughborough College of Technology. He is a Past Chairman of the Editorial Committee and has served on other Institution Committees. Mr. Seaman takes a keen interest in Institution activities.

Mr. G. R. Whitehead, Member, General Manager, of Wolsingham Steel Co. Ltd., has been appointed a Director.

Mr. R. J. Broomer, Associate Member, has relinquished his position of Assistant Technical Director with Messrs. F. J. Ballard & Co. Ltd., Tipton, and has taken up an appointment with Messrs. Stordy Engineering Ltd., Wolverhampton.

Mr. C. Chanter, Associate Member, has relinquished his position of Research Engineer with Wilkinson Sword Ltd., Colnbrook, and has now joined the Atomic Power Constructions Ltd., Research and Development Laboratories, as Planning and Progress Engineer (with the dual position of Personal Assistant to the Principal Research Engineer).

Mr. F. Mannion, Associate Member, has now been been appointed Director of Kay & Co. (Engineers) Ltd., Bolton. He was formerly Production Manager.

Mr. Ian McLeod, Associate Member, has been appointed Technical Director of Lightnin Mixers Ltd. For the last two years, Mr. McLeod has been Technical Director of Stockdale Engineering Ltd. Mr. MacLeod is a former Lord Austin Prize winner.

Mr. D. J. H. Murray, Associate Member, has recently taken up an appointment as a Lecturer in Mechanical Engineering at Lincoln Technical College.

Mr. John W. Saunders, Associate Member, has relinquished his position with I.C.I. Ltd., Alkali Division, and has taken up an appointment as Chief Work Study Engineer at the Imperial Paper Mills Ltd., Gravesend.

Mr. A. G. Thorburn, Associate Member, Machine Shop Manager, Distington Engineering Co. Ltd., a subsidiary of United Steel Companies Ltd., has recently been appointed Quality Control Engineer, responsible to the General Manager for all matters of quality control and inspection.

Mr. A. W. Hart, Graduate, has relinquished his position as Mechanical Engineer at Murphy Radio and has taken up an appointment as Assistant Engineer at Vandervell Products Ltd., Maidenhead.

Mr. G. F. Howden, Graduate, has taken up the position of Production Manager for the Steel Furniture Department at G. A. Harvey & Co. (London) Ltd.

Mr. J. G. Hyland, Graduate, has relinquished his position as Manager of the Safra Aerosol Valve Co. Ltd., Bracknell, Bucks., and has now joined the executive staff of The Metal Box Co. Ltd., London, as Assistant to the Deputy General Manager, Plastics Group.

Mr. John B. Talbot, Graduate, has relinquished his position with C.I.C. Engineering Ltd., Bath, and has taken up an appointment as a Production Engineer on the Engineering Staff of the John Bull Rubber Co. Ltd., Leicester.

Mr. A. Wilkinson, Graduate, has been appointed Lecturer-in-charge of Production Engineering at the Northampton College of Technology.

Hazleton Memorial Library

ADDITIONS

Members are reminded of the following Library rule, which is frequently ignored:

> **"The initial loan period is one month, and borrowers may keep books and periodicals for further periods of one month, if they ask the Librarian, and if no other borrower wants them. Applications for renewal may be made by post or telephone."**

Klein, Josephine. **"The Study of Groups."** *London, Routledge and Kegan Paul,* 1956. 200 *pages. Diagrams.* (International Library of Sociology and Reconstruction.) 21s.

An attempt to acquaint the reader with the materials which had been accumulated in the field of small group studies, that is to say, the study of the formation and structure of small groups of people, and the interactions of their members. Social life is so complex as almost to defy scientific study, but the study of small groups in comparatively simple situations goes some way towards providing a general theory of social life, which could be useful to — amongst others — industrial managers.

Lehrer, Robert N. **"Work Simplification, Creative Thinking About Work Problems."** *Englewood Cliffs, N.J., Prentice-Hall,* 1959. 394 *pages. Illustrated. Diagrams. Tables.* 63s.

The principles and formulae developed by Frederick W Taylor, the Gilbreths and Marvin E. Mundel are carried forward in this book. Mr. Lehrer stresses the human factor in work simplification and the importance of group participation and fatigue reduction. The historical development of the subject is dealt with as well as extensive analysis of work improvement studies, including the motivation, preparation, method, and the relationship of such studies to such topics as automation, electronic data processing, human engineering and operations research.

The author is Editor-in-Chief of the *Journal of Industrial Engineering* and Professor of Industrial Engineering at Northwestern University as well as a consultant to various business and industrial firms. This book is a practical manual and an important addition to the subject of motion study.

Lewis, Kenneth B. **"The Grinding Wheel; A Textbook of Modern Grinding Practice."** *Revised Edition by W. F. Schleicher. Cleveland, Ohio, The Grinding Wheel Institute,* 1959. 527 *pages. Illustrated. Diagrams. Tables.* 35s.

This work was first published in 1951 and the revised edition contains a certain amount of additional information including chapters on Mounted wheels — Reinforced wheels — Automation and advanced mechanisation — Members of Grinding Wheel Institute — Grinding Wheel Institute Technical and other activities. The work as a whole covers the fundamentals of grinding practice, and should be useful to students.

Contents: Wheel shapes and sizes — Grinding fluids — Rough grinding — Cylindrical grinding — Surface grinding — Truing, dressing and balancing — Crush forming and form grinding — Internal grinding — Tool and Cutter Sharpening — Grinding cemented carbides — Disc grinding — Cutting off — Thread grinding — Gear grinding — Roll grinding — Honing — Lapping and Superfinishing — Grinding non-metallics.

Marriott, R. **"Incentive Payment Systems: A Review of Research and Opinion."** *London, Staples Press,* 1957. 232 *pages.* 21s.

A review of the research which has been carried out on incentive payment systems, and of informed opinion based upon practical experience in industry. It compares the views of people in management, trade union and research circles. The author is Assistant Director of the Industrial Psychology Research Group of the Medical Research Council.

Contents: Introduction (Historical background; Some problems of research on incentives and motivation) — Types and classification of incentive payment systems — Advantages and disadvantages of incentive payment systems — The setting of time or work standards — Effectiveness of incentive payment systems — Failures and restriction of output — The total situation and its relation to financial incentives — A general appraisal — Appendix (The basic requirements of incentive payment systems) — Bibliography.

Ministry of Aviation. **"Final Report on CO_2 Shielding of Metallic Arc Welding of Aircraft Steels and Alloys. The Welding of High-Nickel Alloy Sheet."** Prepared by the British Welding Research Association under Ministry of Supply Contract 6/Aircraft/13832/CB 6(b). *London, the Ministry, January,* 1960. 9 *pages. Diagrams. Graph.*

Murphy, Gordon J. **"Basic Automatic Control Theory."** *Princeton, London, etc. Van Nostrand,* 1957. 557 *pages. Diagrams. Tables.* 67s. 6d.

This volume evolved from lecture notes given to senior and first-year graduate students in engineering and physics at the University of Minnesota. It represents a comprehensive treatment of the most modern concepts of automatic control theory. The analysis and synthesis of linear control systems having fixed, lumped parameters and subject to specifiable input commands and disturbances are fully described. Many practical input commands and disturbances are fully described. Many practical examples are given to illustrate theory. The physical analogies and the characteristics of common control-system components are discussed. The principles of operation and the use of analogue computers are also included.

Nixon, Floyd E. **"Principles of Automatic Controls."** *London, MacMillan,* 1958. 409 *pages. Illustrated. Diagrams.* 30s.

As stated, " this book is concerned with the design of a control system from the analytical viewpoint ". It covers all the most recent methods used in control system design.

Contents: Elementary control systems — The Laplace transform — Frequency response analysis methods — Stability criteria — Numerical integration methods — Operation of automatic computers — Transient response analysis and non-linear elements with an Appendix including sections on, *inter alia* — Runge-Kutta numerical integration method — Design data for cascade functions — Complex numbers — Derivation of the Nyquist criterion.

Paton, E. O. *Ed.* **"Automatische Lichtbogenschweissung."** *Halle, Marhold,* 1958. 469 *pages. Illustrated. Diagrams. Tables.* In German.

This work is considered to be a classic Russian work on automatic arc welding. The translation into German was made by Prof. Dr. Ing. H. Neese, and the original book was published in 1953.

The submerged arc process of welding is given a most detailed and comprehensive treatment. The first four sections of the book deal with this process which was developed by the E.O. Paton Institute for Electric Welding of the Ukranian Academy of Sciences in Kiev. The electrical thermal and metallurgical processes, the technique, technology, equipment and practical application of the process are covered. Details are given of its application in the construction of mining equipment, boiler equipment, motor vehicles, and in the ship-building and metal industries. The last section of the book covers other aspects of welding such as gas-shielded arc welding. This work should prove an invaluable aid to both student and engineer.

Perry, Henry Alexander. **"Adhesive Bonding of Reinforced Plastics."** *London, New York, etc., McGraw-Hill,* 1959. 275 *pages. Illustrated. Diagrams. Tables.* 68s.

Written for those interested in the design and asembly of structures and products by means of adhesives, and in particular those engaged in the manufacture of glass-fibre reinforced plastics products.

Contents: Introduction — Mechanics of adhesive joints — The statistical point of view — Laminated resins and adhesives — The theory of adhesives — General properties of adhesives — Mechanical testing of adhesives — Adhearand materials — Adhesive bonding process factors — Adhesive bonding equipment — Quality control of adhesive bonds — Design of adhesive joints.

Pronikov, A. S. **"Wear and Life of Machine Tools."** *Moscow,* 1957. 274 *pages. Diagrams.*

The design of machine tools in special reference to accuracy and long life.

Purchasing Officers Association, London. **"A Guide to Aluminium,"** by L. V. Chilton. *London, Aluminium Development Association,* 1960. 29 *pages. Tables.* (A.D.A. Reprint series No. 85. Reprinted from *The Purchasing Journal,* July - October, 1959, by permission of Purchasing Officers Association.)

Contents: Ores and production methods — Properties and methods of use of aluminium and its alloys — Major fields of application of aluminium.

Ryan, Paul W. S. **"Engineering Administration."** *London, Angus & Robertson,* 1959. 78 *pages.*

Written primarily as a textbook for students in the Civil Engineering School of the University of New South Wales, this work deals with administration in general and in particular, with administration of civil engineering projects.

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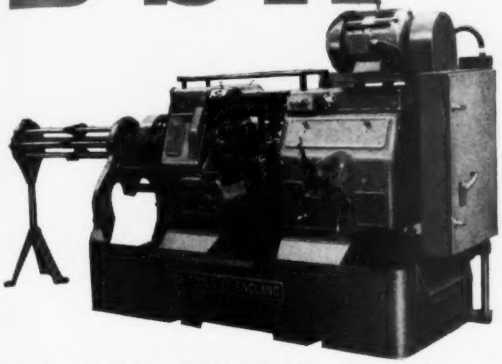

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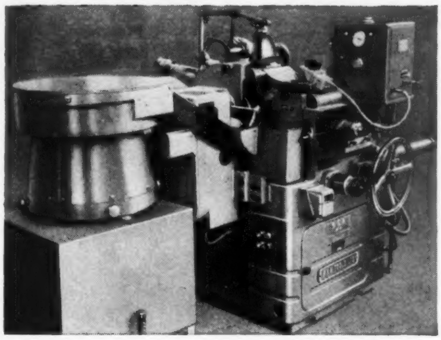

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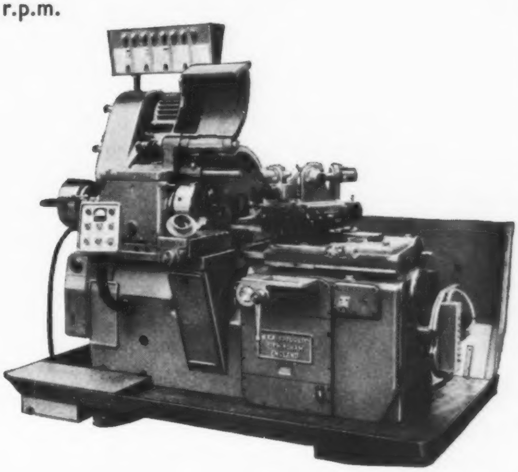

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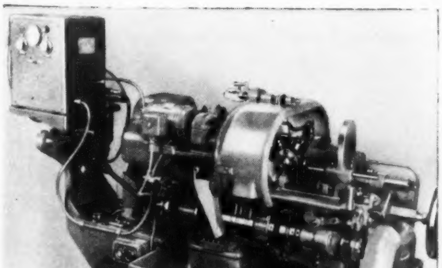

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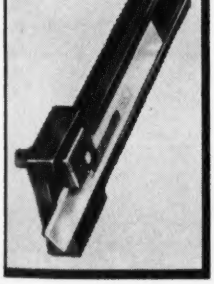
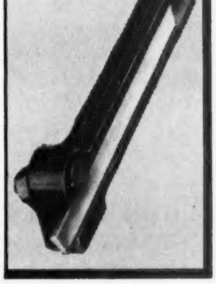
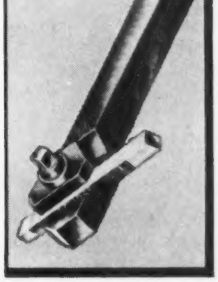

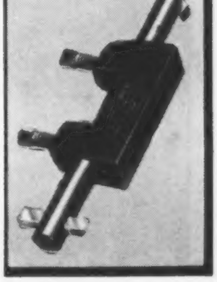

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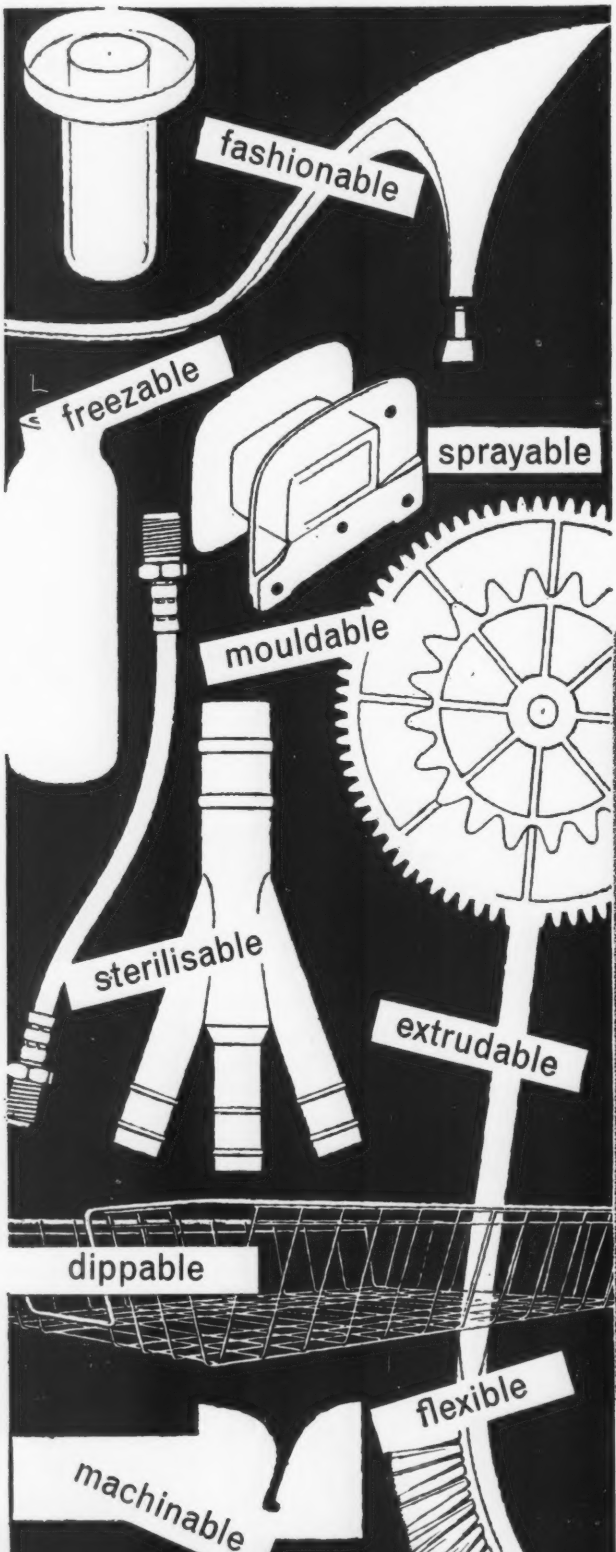
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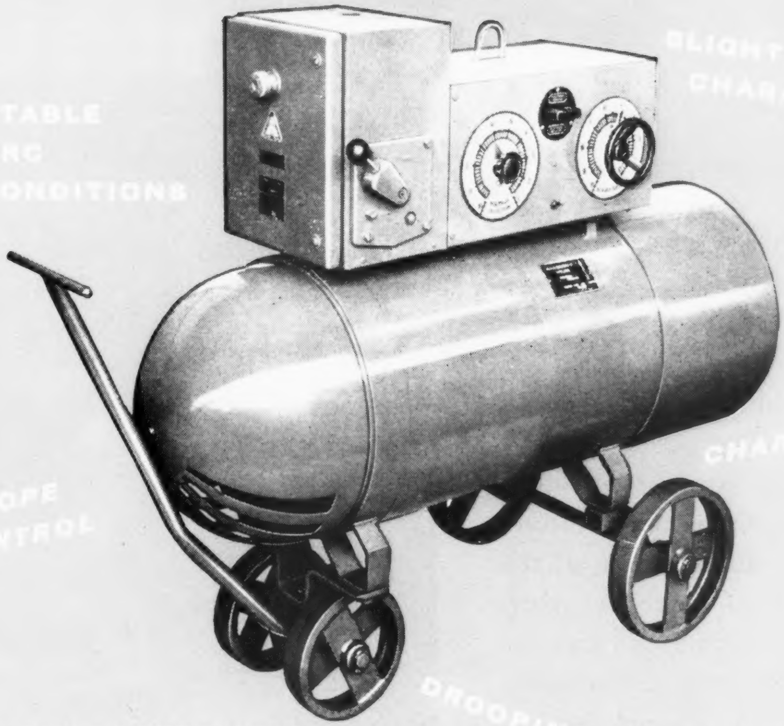

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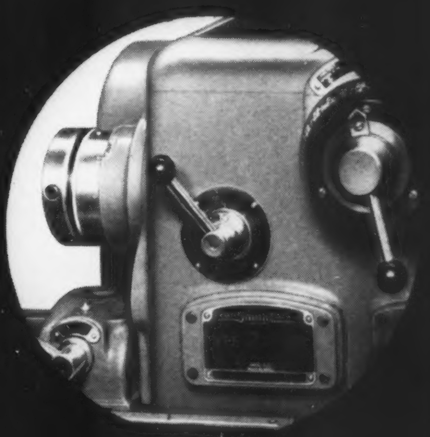

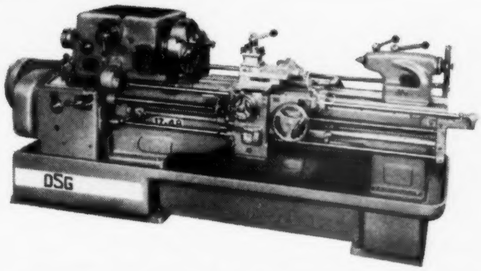
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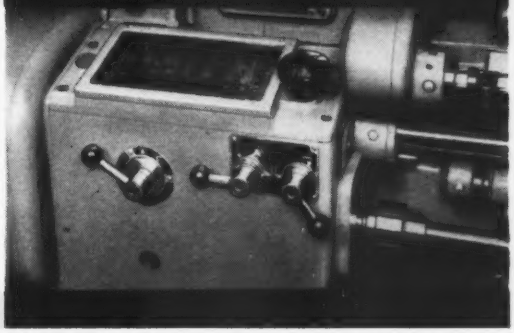

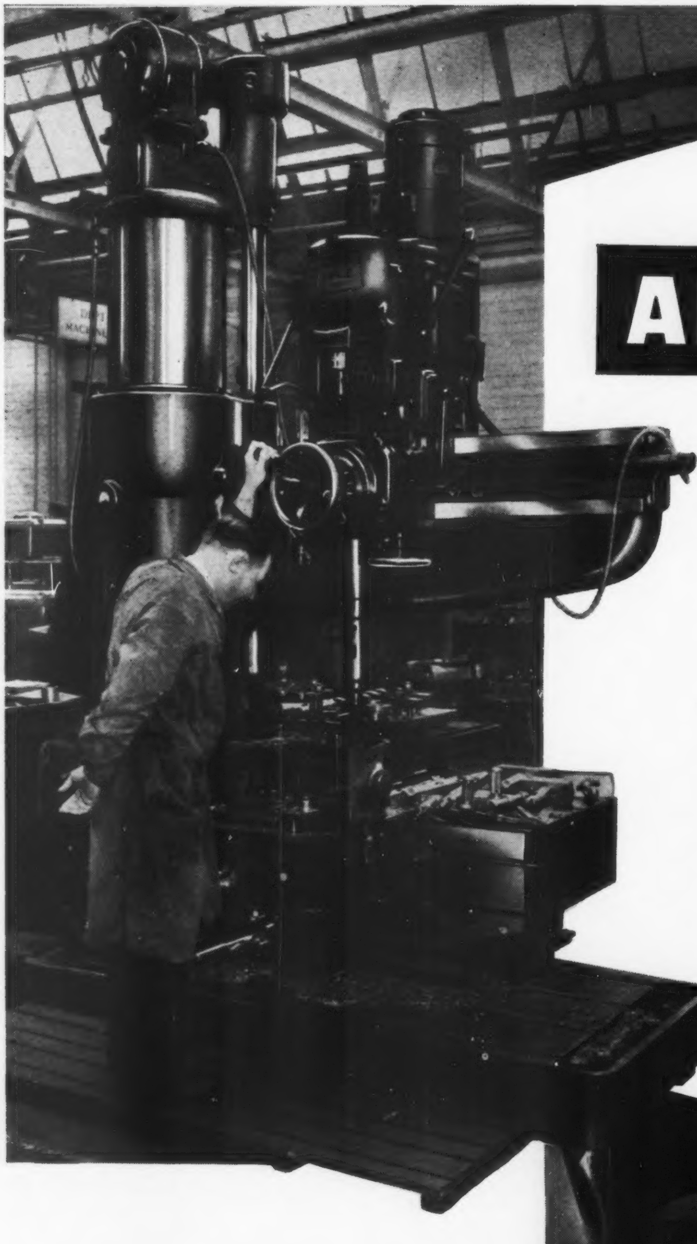

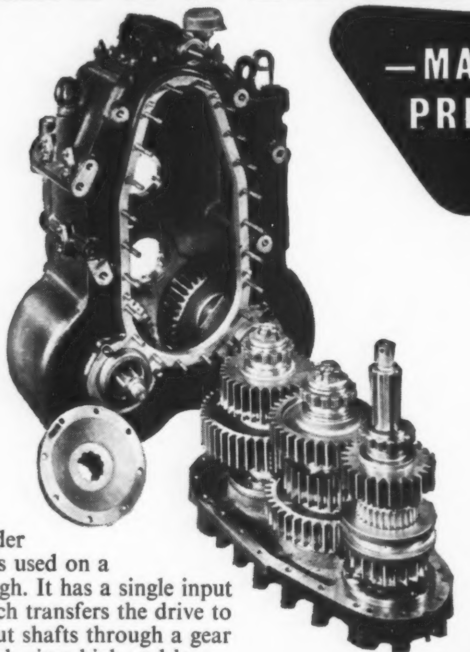

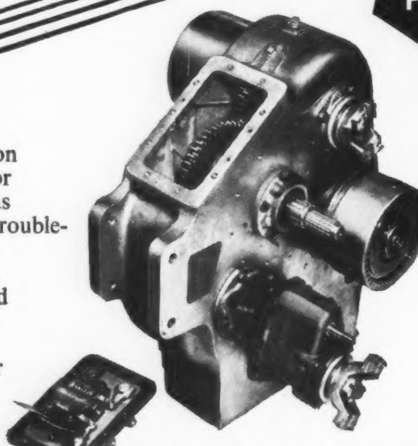

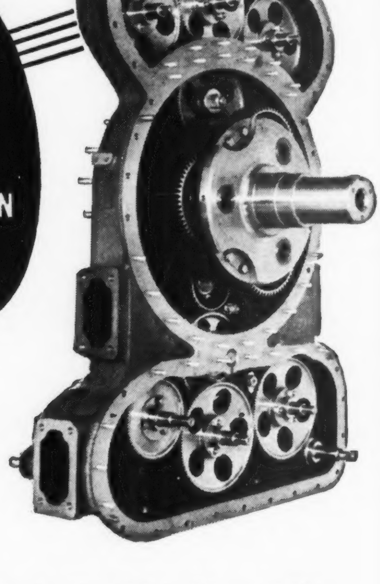

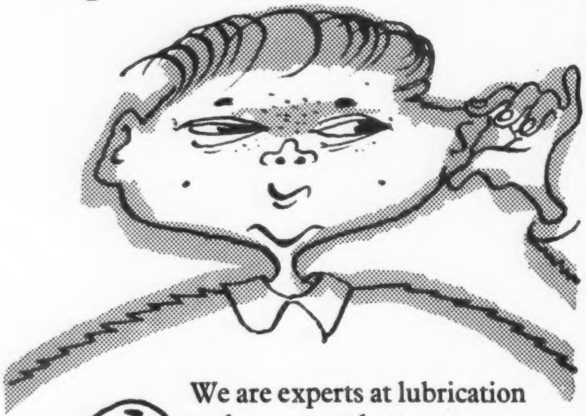

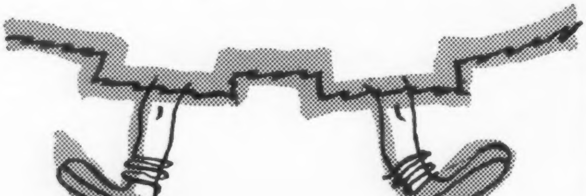

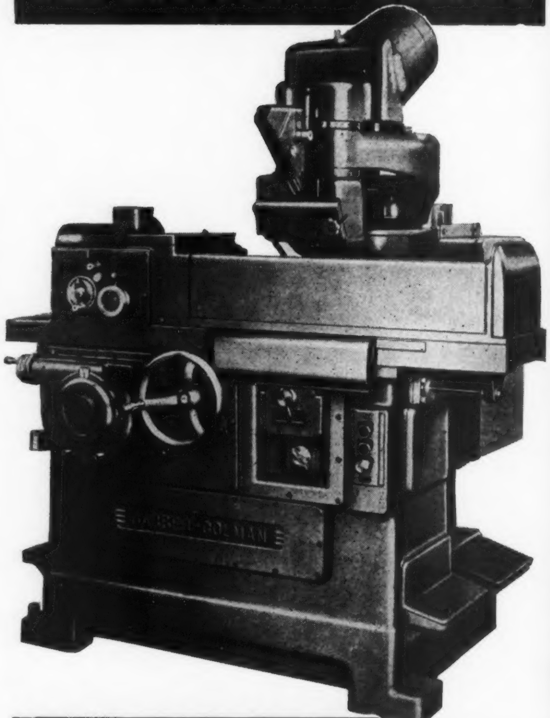

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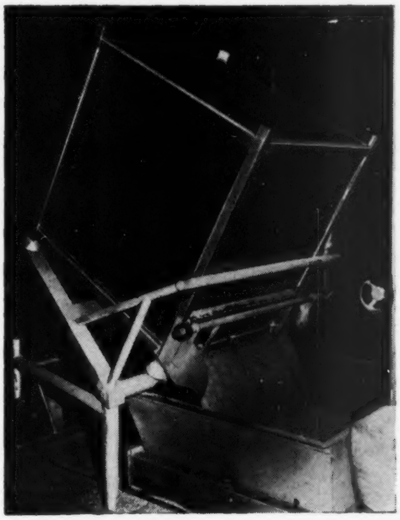

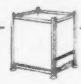

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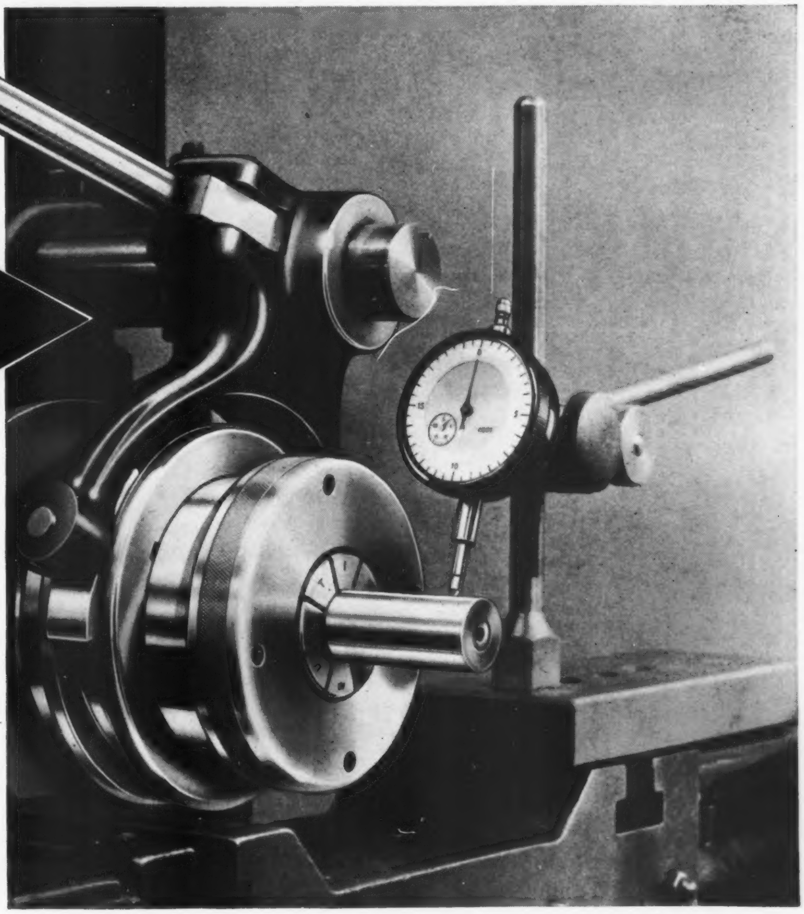

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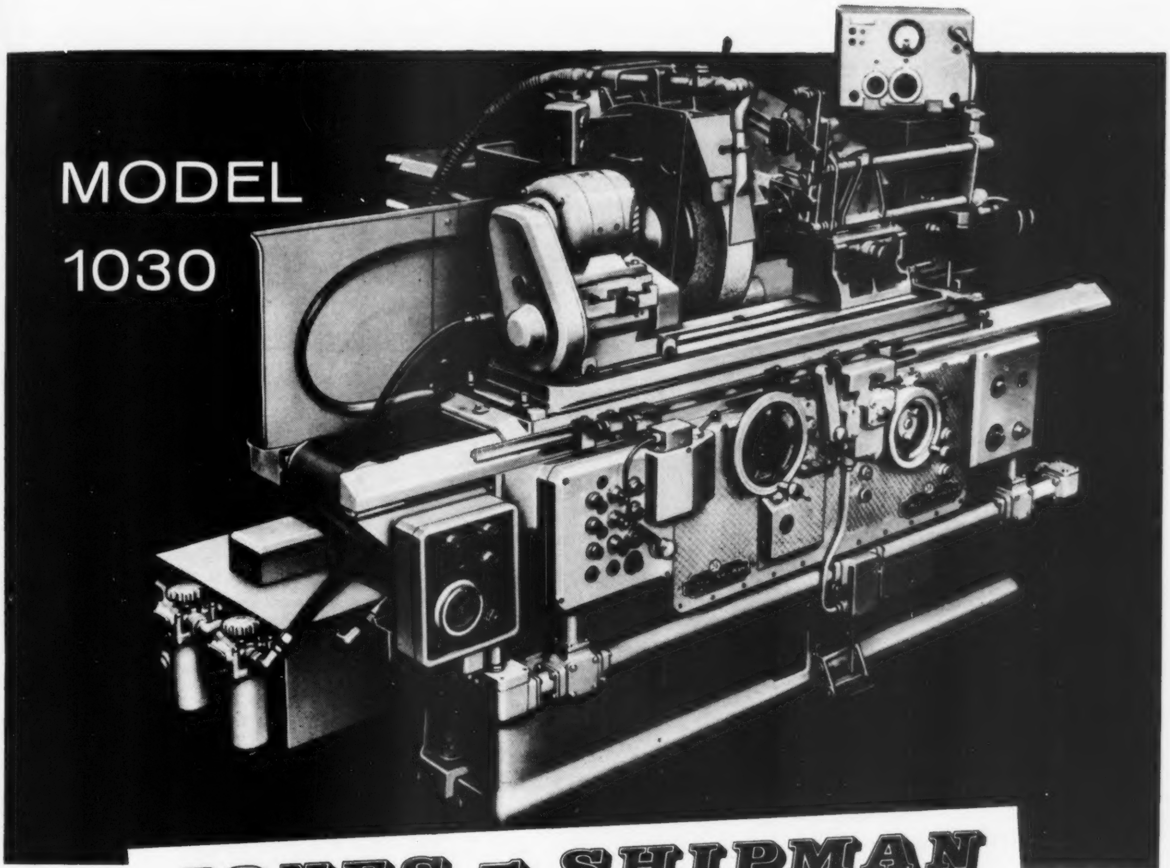

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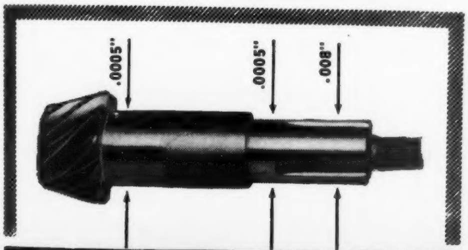

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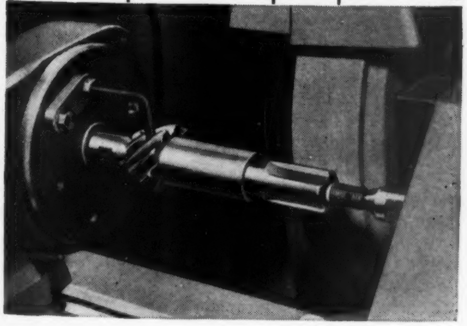

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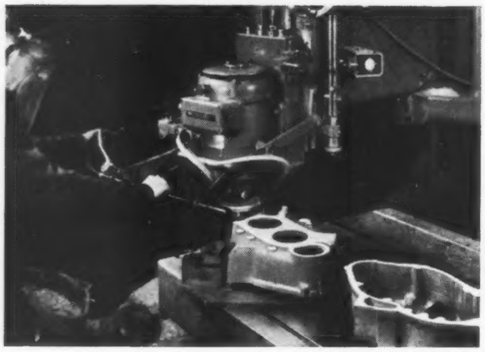

Some users of Wadkin Heavy Duty Articulated Arm Routers, Type LC

Wadkin Heavy Duty Articulated Arm Router, LC face-milling gearbox end covers. Photo by courtesy of Ruston & Hornsby Ltd., Grantham.

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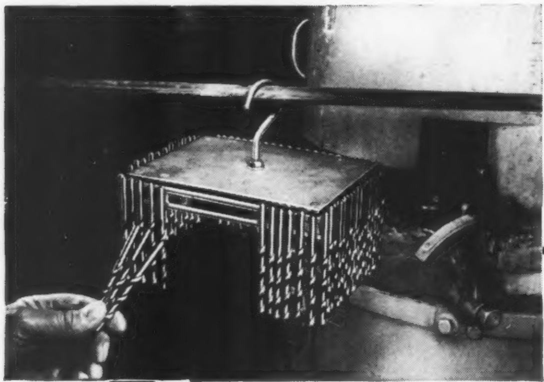

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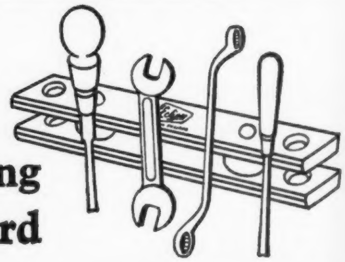

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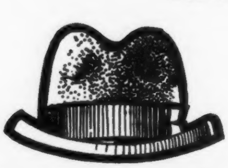
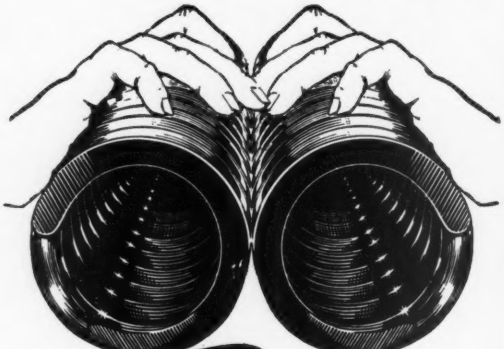


Looking in the right direction



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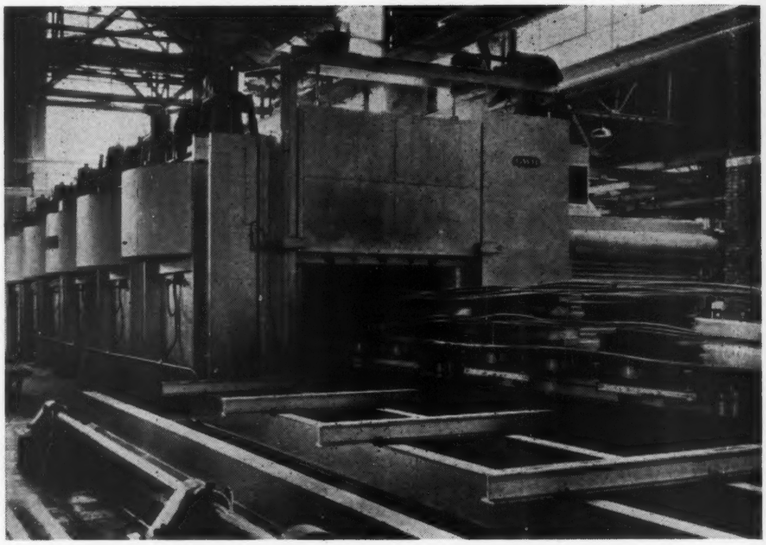

Batch Type Furnace installed, with slow cooling chamber at right, at Northern Aluminium Co. Ltd. for annealing aluminium slabs prior to cold rolling.

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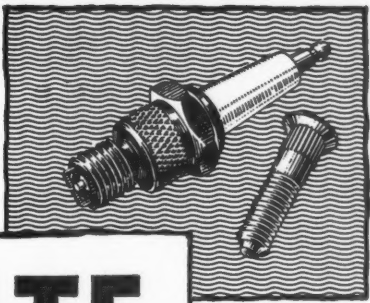

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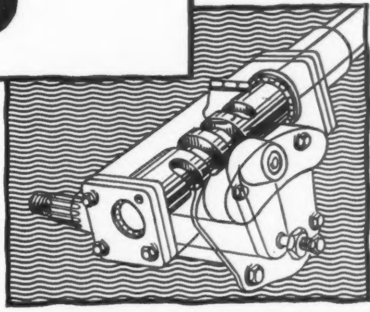

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Coils may be split if required.

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0.550" to 1.000" in 900 lb. coils.
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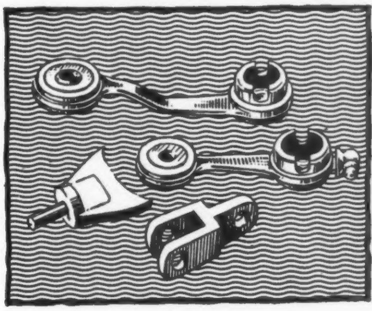

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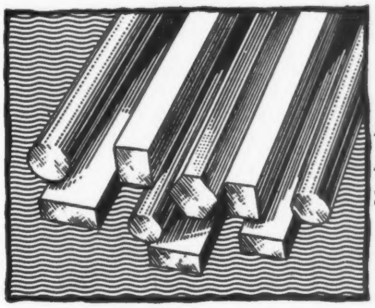

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